JOURNAL OF THE AMERICAN

ROCKET

SOCIETY

A journal devoted to rocket technology and the jet propulsion sciences

STACKS

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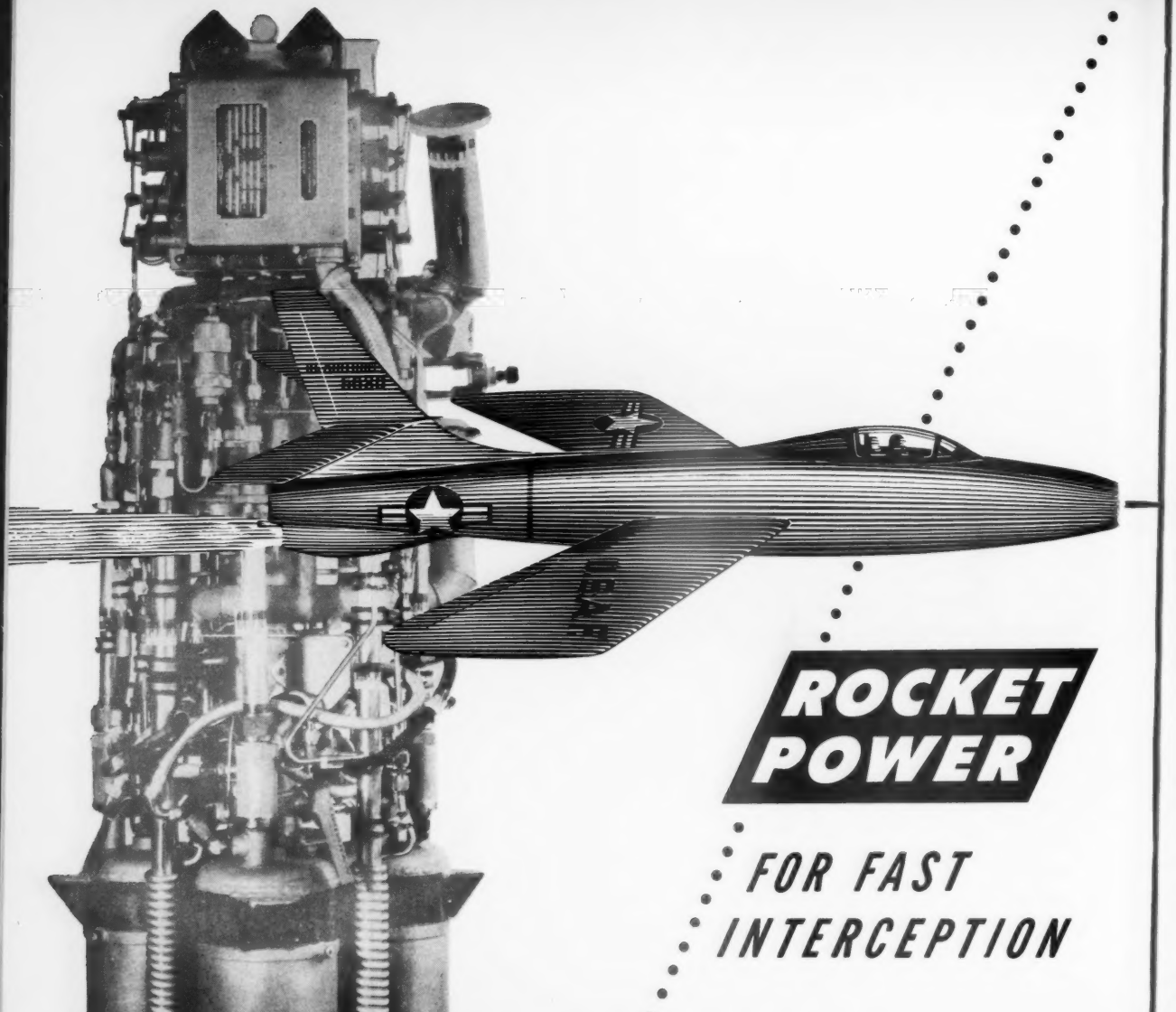

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The Journal of the American Rocket Society is devoted to the advancement of the field of jet propulsion through the publication of original papers disclosing new knowledge and new developments. The term "jet propulsion" as used herein is understood to embrace all engines that develop thrust by rearward discharge of a jet through a nozzle or duct, and thus includes systems utilizing atmospheric air and underwater systems, as well as rocket engines. The Journal is open to contributions, either fundamental or applied, dealing with specialized aspects of jet and rocket propulsion, such as fuels and propellants, combustion, heat transfer, high temperature materials, mechanical design analyses, flight mechanics of jet-propelled vehicles, astronautics, and so forth. The Journal endeavors, also, to keep its subscribers informed of the affairs of the Society and of outstanding events in the rocket and jet propulsion field.

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Represents the jet propulsion profession before the public, promotes interest in jet propulsion and its applications, encourages the formation of regional chapters and student branches where technical conferences may be held.

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Encourages and aids those actively working in this field by organizing national and regional technical meetings where contributed and invited papers are presented and discussed.

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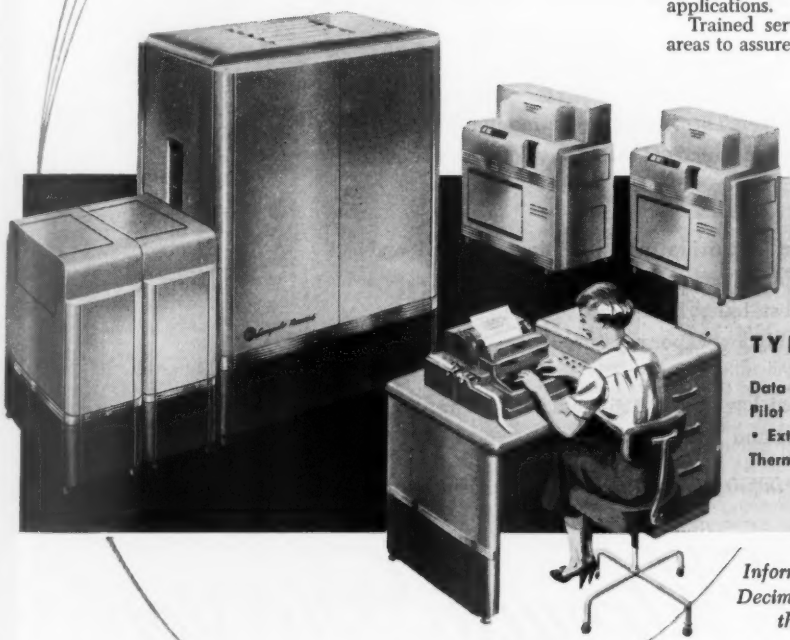

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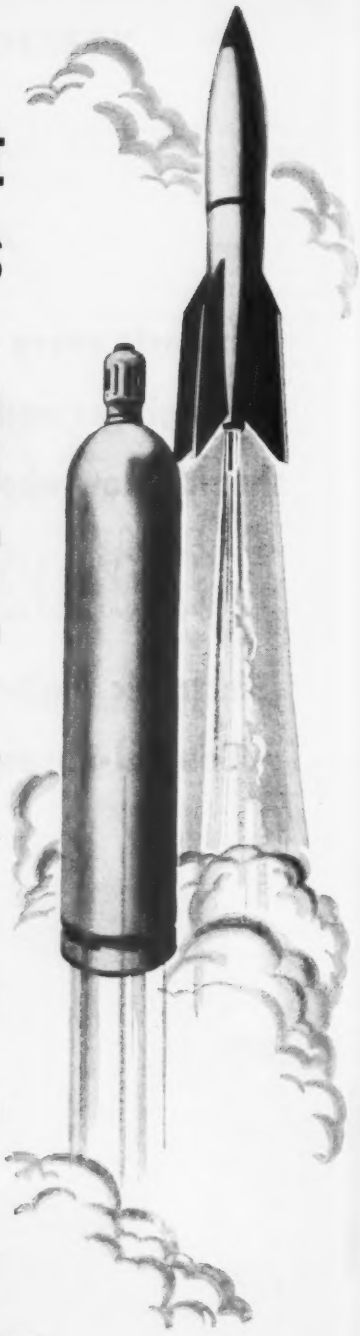

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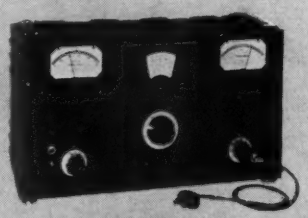

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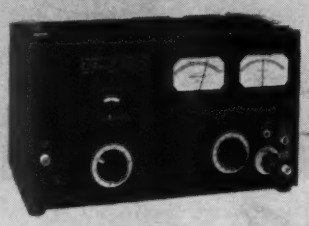

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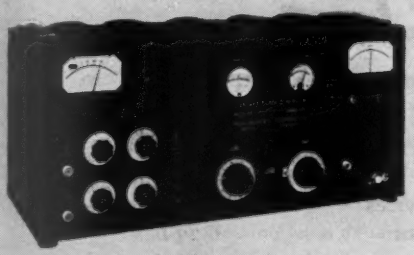

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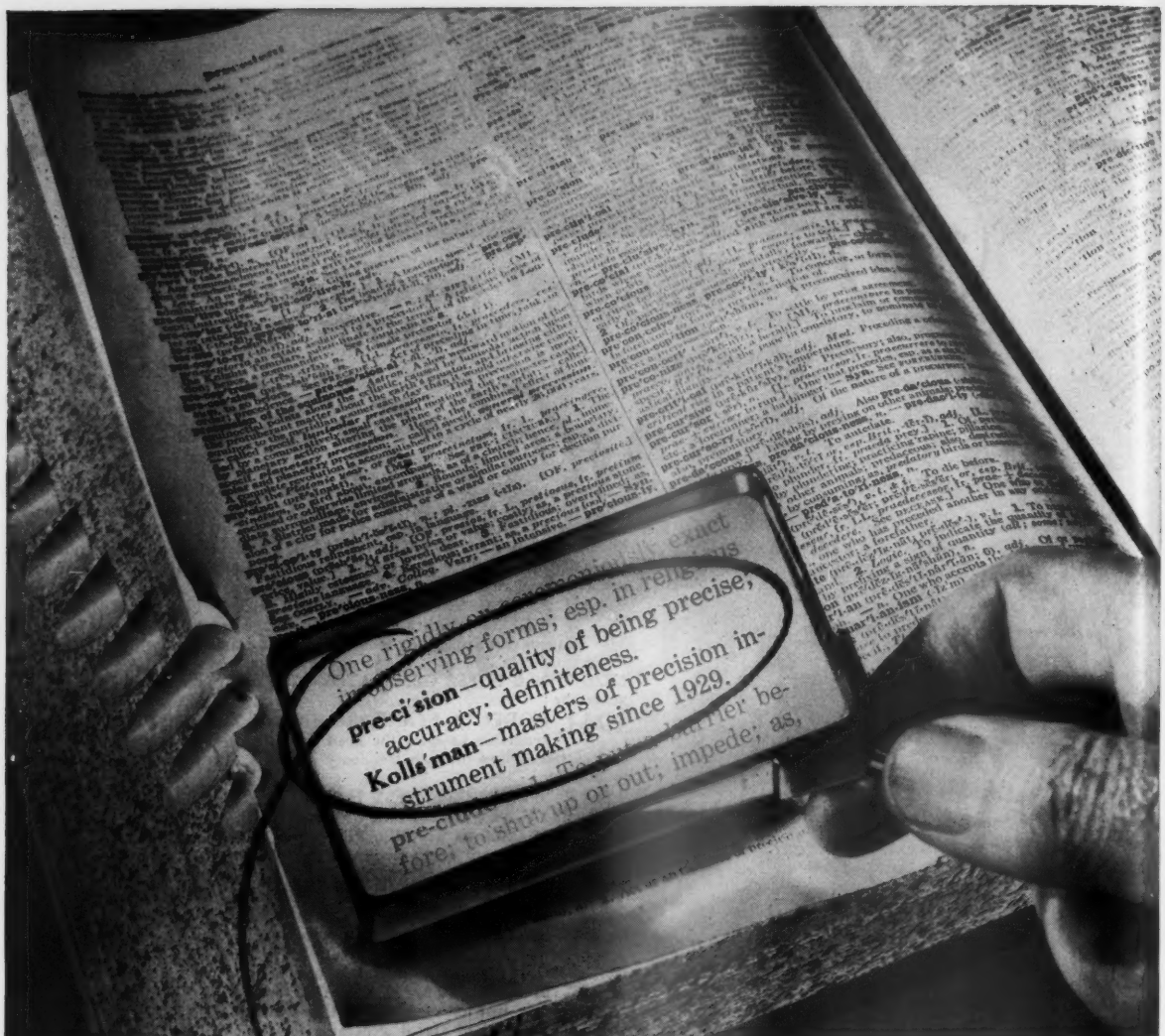
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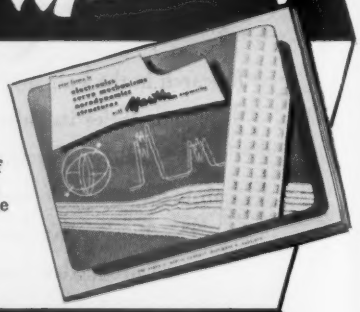

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The Instrumentation Issue

THE Editors of the JOURNAL OF THE AMERICAN ROCKET SOCIETY take pride in offering this issue to its readers. The issue is the largest ever published by the Society from the standpoint of technical content. It contains the greatest amount of advertising ever sold in a single issue. It will undoubtedly command the broadest reader attention of all previous issues, because of its special coverage.

The idea for this issue was generated about one year ago, and active planning began in June 1952. According to plan, each article was specially invited from an acknowledged authority on the particular subject. Taken together, the collection of articles forms a coherent and orderly treatment of every phase of instrumentation important in rocket and jet propulsion development.

The uniformly cooperative response of the authors to the invitations was gratifying indeed to the Editors. They exerted every effort to meet the Editors' requests (the unreasonable ones as well) regarding coverage, style, illustrations, bibliography, etc.; even the imposed deadlines were met! Advance indications are that these efforts on the part of the authors will receive favorable recognition, expressed through the active use that will be made of this issue by its readers, not only in the immediate future but also as a reference work for a long time to come.

It is a pleasure to record here that the paid circulation of this issue is more than twice as great as that of the corresponding issue almost two years ago, when the new series was inaugurated. This is an extraordinary record of growth testifying to the acceptance of the JOURNAL by the profession. For this particular issue, an extra large print order was placed to take care of single copy purchases which are expected to be unusually heavy.

Most of the credit for the preparation of this special issue is due Dr. Irvin Glassman, Assistant Editor of the JOURNAL, who served as its editor from its inception. His remarks which appear on this page are intended to serve as an explanation of the arrangement of topics in the issue and a guide to items of special interest that can be found in the various articles.

MARTIN SUMMERFIELD
Editor-in-Chief

IN reviewing and comparing old and new developments in jet propulsion instrumentation, this issue covers the significant steps required in any given experimental analysis, namely: transposing the significant physical phenomenon into some measurable impulse; transmitting or telemetering this impulse to a recording unit; recording the signal on an instrument having the response and accuracy required by the experiment; and, finally, reducing the data obtained from the recorders in the most convenient manner for application to the analysis.

In discussing the parameters of interest (thrust, pressure, flow rate, temperature, gas composition, etc.) some articles bring to light interesting trends toward techniques developed in other fields and not previously applied to problems in jet propulsion. Conversely, other articles discuss instruments which have been developed primarily for specific jet propulsion problems and which are finding application elsewhere. For example, the water-cooled, double diaphragm type pressure pickup (v.i., Li) developed for studies of combustion instability in rockets is applicable to studies of explosions. Similarly, the true mass flowmeter which is discussed in technical detail in the article by Grey and Liu is of interest in other fields as well as jet propulsion. The comprehensive discussion of temperature measurement with immersion type instruments (v.i., Fiock and Dahl) presents information and late developments which will undoubtedly command wide interest. In particular, the paper deals with the corrosion and mechanical stress problems encountered in the use of thermocouples in jet propulsion engines, important matters normally not covered in the literature. Complementing the article on immersion instruments is the constructive comparison of optical methods for combustion temperature measurements (v.i., Penner and Dyne).

The necessity for making measurements in guided missiles and rockets being used for high altitude research has significantly brought about the development of the relatively new field of radio telemetry. Telemetering equipment is at the present time an essential part of any research vehicle. The discussion of systems in current use in the article by Cummings and Newberry is supplemented by a highly significant analysis of requirements for other systems. The article on telemetry should prove of considerable interest, for telemetry may find a significant place in ground installations, just as industrial television is proving a useful tool in engineering and research operations.

The proper recording of a signal or event is as important as using the proper transducer. The emphasis of research in jet propulsion today seems to require rapid response instruments and the rapid recording of events; consequently, there are included discussions of high-speed recording instruments (v.i., Jones) and motion picture cameras (v.i., Berman and Scharres). The effective comparison of response and versatility of various commercial recording instruments, as presented by Jones, is intended to assist the reader in a proper choice for his purpose. In the article, emphasis is placed on magnetic tape recording, a method that is being used increasingly as a primary and secondary recording means in fast response systems.

Reduction of large quantities of recorded data by use of machines has proved rapid and economical. While it is not within the scope of this issue to discuss in detail machine computations, it seemed appropriate to include a presentation (v.i., Beighley and Cheatham) of their use in rocket research as one of the general procedures involved. Various types of punched-card machines presently available are examined.

In discussing devices ranging from transducers through machines for data reduction, many of the authors found it worth while to name commercially available units in order to illustrate the principles involved. Opinions of specific instruments, as expressed by the individual authors, are solely their own and not necessarily those of the Editors or of the Society. The selection of a particular manufacturer's product for discussion does not necessarily signify that it is the opinion of the authors (or of the Editors of the JOURNAL) that this product is the best or only device available. It is not the purpose of the issue to serve as a catalogue of devices on the market, but rather to serve as a starting point for a more complete investigation by scientists with specific instrumentation problems.

IRVIN GLASSMAN
Assistant Editor

Dynamic Pressure Measuring Systems for Jet Propulsion Research

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A very important problem in present-day rocket research is the investigation and correction of undesirable pressure oscillations that occur in the combustion chamber and nozzle of a rocket motor. These pressure fluctuations are capable of producing widespread destruction and occur in a frequency range between 100 and 2000 cps. A suitable pressure indicator should have a natural frequency above 10,000 cps if the measurement of these pressure variations is to be relatively free from dynamic error. The indicator must also be capable of dissipating heat at a rate of 10 Btu per sq. in. per sec in order to withstand the extreme heats encountered in rocket motors. In addition, the performance of the indicator must be relatively independent of temperature, which may vary over a wide range within the rocket. The design and performance of two types of water-cooled diaphragm pressure indicators are discussed and compared in detail. It is concluded that the strain-gage diaphragm indicator is presently superior; however, further improvements are still required. Other signal generating systems are also discussed.

Introduction

IDEALLY, a rocket motor is a power plant which develops thrust by the discharge of gases from a constant-pressure gas generator. In practice, however, this desirable constant-pressure running condition is seldom realized even with precisely controlled operating conditions and careful design. Undesirable pressure oscillations usually occur superimposed upon the constant working pressure of the gas generator. These oscillations exist as a result of the dynamic effects of fuel flow through the injector, dynamic properties of the gas in the combustion chamber, and the time delay of the combustion process (1).[2]

These pressure variations contribute to lowering the operating efficiency of the rocket. When the pressure oscillations increase in magnitude, failure of mechanical parts becomes more probable due to excess heat transfer resulting from turbulence associated with the pressure fluctuations. A knowledge of this pressure fluctuation is invaluable in finding means whereby this combustion instability may be eliminated.

Pressure information of this nature must include not only a time history of the magnitude of the pressure variations, but also the relative phases between the pressures at each location desired inside the combustion chamber and nozzle. Dynamic pressure measurement is thus an important phase of rocket research.

Fig. 1 is a functional diagram of a typical pressure measuring system. The functional name of each component is identified in the individual blocks. In this arrangement, the pressure to be measured is transmitted through the input coupler to the pressure receiver. The input coupler may merely be a length of tubing. The pressure receiver consists of a receiving element which actuates the signal generating system. The output of the signal generating system is a signal proportional to the measured pressure, usually in electrical form. This signal is coupled to the indicating system by suitable amplifiers and isolation circuits which are grouped together as the coupling system. The design of pressure measuring instruments, suitable for the use in rocket research, involves proper matching of the performance of these components.

The Input Coupler

A rocket motor is a high-power prime mover which operates by the combustion of high heat content fuels, subjected to pressures ranging from a few hundred to over a thousand pounds per square inch (2). A major problem in the design of rockets is the prevention of overheating of the mechanical parts which directly contact the propellant whose temperature often exceeds 6000 F. This problem becomes very acute in the design of pressure measuring elements, since these elements are generally quite delicate.

For the measurement of static pressure, the input coupler usually consists of a long tube which serves as a heat barrier between the chamber and receiving element.

In dynamic pressure measurement, however, dynamic errors are introduced by such an input coupler (3). For large rates of change of pressure, even a short length of tubing, say $^1/_2$ in., may be objectionable.

McCullough (4) has demonstrated, in a series of tests, the effect of various lengths of tubing on the measurement of pressure in the cylinder of an internal combustion engine. A flush-mounting receiving element was recommended for internal combustion engine research, on the basis of these tests. For rocket operation, the rate of change of pressure

[1] Research Associate.

[2] Numbers in parentheses refer to the References on page 127.

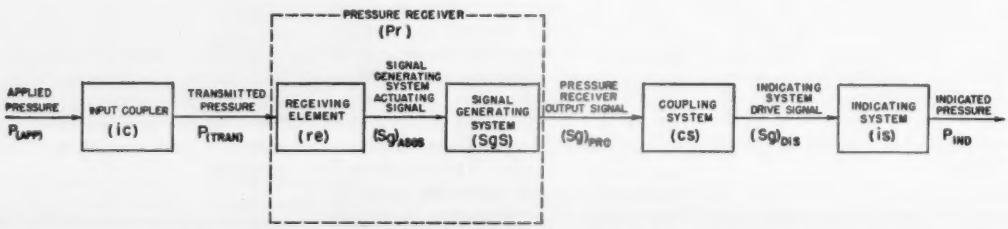


FIG. 1 FUNCTIONAL DIAGRAM OF A TYPICAL PRESSURE MEASURING SYSTEM

during the "screaming condition" is of the same order of magnitude as that in the cylinder of an internal combustion engine. For this reason, the use of tubing of sufficient length to serve effectively as a heat barrier would usually be objectionable from the standpoint of dynamic error.

The Pressure Receiving Element

The use of flush-mounted pressure receiving elements in rocket research requires that the element have efficient cooling. Zucrow and Beighley (2) have reported that the heat transfer rate in a typical rocket engine is between 1 to 6 Btu per sq in. per sec. Higher local heat dissipation rates may be found in certain spots due to the fact that the heat dissipation is not necessarily uniform. Allowing for this with a margin of safety, it may be concluded that pressure receiving elements suitable for rocket research must be supplied with a cooling rate of approximately 10 Btu per sq in. per sec.

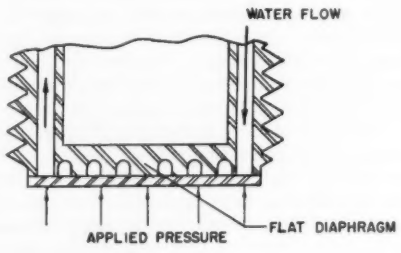
One type of pressure receiving element designed for flush-mounting employs water cooling (5). The element consists of a flat diaphragm which is grooved on the inside to provide a passage for the water, as shown in Fig. 2. This type of cooling system was found to be quite satisfactory in internal combustion engine cylinders where the temperature is relatively low. However, for use in rockets, the cooling provided by this means was found to be inadequate. One possible reason for this is that only a portion of the area of the diaphragm is contacted by the cooling medium.

A second type (6, 7) of water-cooled pressure receiver, developed especially for use in rocket research, is shown in Fig. 3. This unit consists of two thin catenary diaphragms which are clamped to the body of the receiver. A force transmitting ring is placed between the diaphragms and transmits the input pressure to the strain generating tube. This tube is mounted rigidly at one end so that the strain in the tube becomes proportional to the applied force. A constant reference pressure is applied to the upper diaphragm so that the force transmitted to the strain generating tube is proportional to the difference between applied and reference pressures. Cooling is accomplished by pumping water between the diaphragms. The water is guided through and around the force transmitting ring. Thus every portion of the thin diaphragm and force transmitting ring surfaces makes intimate contact with the cooling medium, with the exception of the small circle of contact between the ring and the diaphragm. Cooling efficiency is thus increased over the receiver of Fig. 2.

The catenary diaphragm is such that, under pressure, pure tensile stresses are developed in the diaphragm material; this gives high structural efficiency. For exampie, a catenary diaphragm with a $^1/_2$-in. diameter is about $^1/_8$ the thickness of a flat diaphragm having the same strength. The greatly reduced thickness of the catenary diaphragm makes it extremely flexible; the elastic stiffness of a diaphragm varies as the cube of its thickness.

Due to the large flexibility of the catenary diaphragm, almost all of the elastic restraint of the pressure receiver is supplied by its center support. This center support may be a strain generating tube or consist of piezoelectric material. The latter produces an electrical signal proportional to the applied pressure, whereas strain gages (or capacitance gages) may be employed as the signal generating means in the former.

A sectional view and photograph of the water-cooled catenary diaphragm using strain-gage generating means are shown in Figs. 4 and 5. Test results of this type of pressure measuring device revealed that it has great possibilities for use in rocket research. One unit was constructed using a diaphragm thickness of 0.004 in. This unit performed satisfactorily at temperatures estimated up to 5000 F, over an extended period of time. This same unit was destroyed after running for about one second under screaming conditions, where the estimated temperature was 6000 F. Excellent pressure indication was observed on the screen of an oscilloscope prior to destruction. One reason for failure was the extreme operating conditions to which the pressure receiver was subjected. During this test, the pressure receiver was installed in the nozzle section where the tempera-



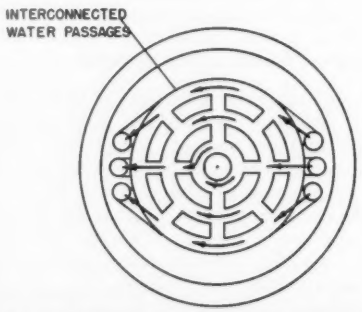
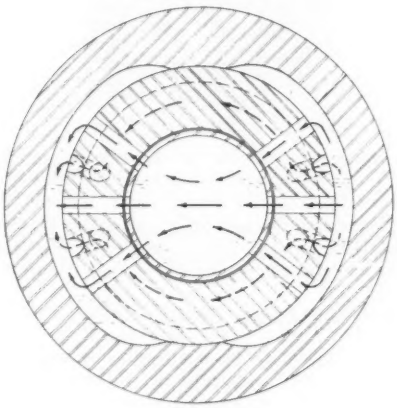


FIG. 2. SCHEMATIC DIAGRAM OF A FLAT DIAPHRAGM WATER-COOLED PRESSURE RECEIVING ELEMENT



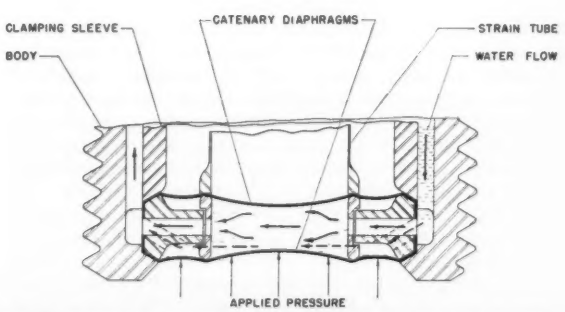


FIG. 3 SCHEMATIC DIAGRAM OF A CATENARY DIAPHRAGM WATER-COOLED PRESSURE RECEIVING ELEMENT

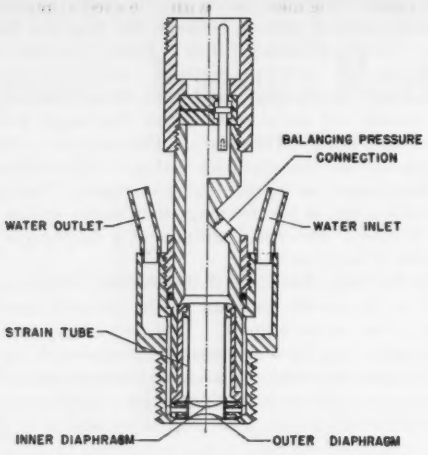


FIG. 4 SECTIONAL VIEW OF A WATER-COOLED DIFFERENTIAL PRESSURE INDICATOR

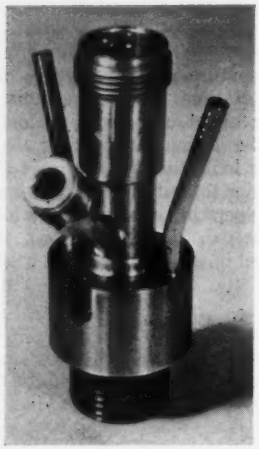


FIG. 5 PHOTOGRAPHIC VIEW OF AN 18-MM WATER-COOLED CATENARY DIAPHRAGM PRESSURE INDICATOR

ture is most extreme; it was later discovered that the combustion chamber of the rocket motor was burned through in this test.

Dynamic Performance

The dynamic performance of pressure measuring elements can be represented by a second-order (0; 0,1,2) system (8). After this fact is determined, it is only necessary to specify the damping ratio and natural frequency of the system to determine its complete dynamic performance. The damping ratio of a high natural frequency element is usually small, in the order of 0.05 to 0.10. Under this low damping condition, the frequencies of measured pressure variations must be limited to less than $^1/_5$ of the natural frequency, if excessive dynamic errors are to be avoided. At this frequency ratio and lower, the ratio of dynamic error to signal varies approximately as the square of the frequency ratio. The pressure waves inside the combustion chamber have many different modes. These modes consist of frequencies varying from below 100 cps up to 2000 cps (1). The natural frequency of the pressure receiver must be in the region of 10,000 cps to cover this range.

High natural frequencies may be attained by using a receiving element with a small effective mass. Of the two types of pressure measuring methods previously discussed, the catenary diaphragm is usually lighter because of its greater structural efficiency. However, the mass introduced by water-cooling causes a reduction in natural frequency in both cases. An alternate method of increasing the natural frequency is to increase the stiffness of the elastic support. Unfortunately, this is accompanied by a proportionate decrease in static sensitivity. In general, reduction in static sensitivity makes the device more susceptible to temperature interference. Thus, two criteria of design for pressure receivers are that they have a sufficiently high natural frequency and sufficient freedom from interference effects. This is sometimes quite difficult to achieve in practical design. In general, a compromise must be made between these two opposing factors.

The dynamic parameters of high natural frequency pressure receivers may be measured by the use of a shock tube. A shock tube is capable of applying a very rapid change in applied pressure to the receiver, closely approximating a step function. This step function in pressure produces a transient response, a typical record of which is shown in Fig. 6. This

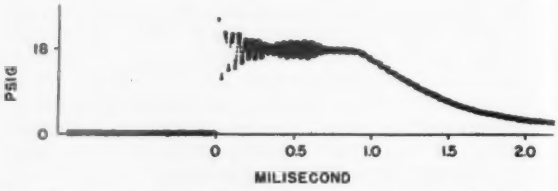


FIG. 6 TYPICAL SHOCK TUBE RESPONSE OF A CATENARY DIAPHRAGM PRESSURE INDICATOR

was obtained by means of a high-speed oscilloscope camera. From the transient response it is possible to obtain both the natural frequency and damping ratio of the pressure receiver. A $^7/_{16}$-in. diam catenary diaphragm water-cooled pressure receiver has a natural frequency of 20,000 cps, and a damping ratio of 0.10. This receiver is capable of measuring pressure frequencies up to 5000 cps with a dynamic error of less than 7 per cent.

In general, the deflections of a $^1/_2$-in. pressure receiving element having a natural frequency greater than 10,000 cps never exceed 0.001 in. under full rated pressure. These small displacements can easily be confused with deflections due to other causes. In particular, pressure measuring systems for rocket research are greatly affected by temperature disturbances caused by the extreme thermal effects peculiar to rocket engines.

Temperature disturbances manifest themselves in two forms: they may produce a deflection in addition to that produced by the input pressure, and/or they may change the static sensitivity of the pressure receiving element between displacement and applied pressure.

The catenary diaphragm pressure receiver is distinguished by its low response to temperature disturbances. This is brought about by incorporating the principle elastic restraint behind the diaphragm where it is protected, to some extent, from temperature changes. This is a further reason for using this type of pressure receiver in rocket research.

The Signal Generating System

It has been indicated that the deflections of high natural frequency pressure receiving elements are generally quite small, due to the high stiffness required. It is thus necessary that the signal generating system be highly sensitive. For practical reasons, the signal generating system is usually incorporated with the receiving element to form the complete pressure receiver, as shown in Fig. 1. The signal generating system normally is not in direct contact with the hot gases of the rocket combustion chamber and nozzle; it is, however, subject to the temperature variations in the shell or wall of the rocket. It must, therefore, be relatively insensitive to temperature changes.

TABLE 1 RELATIVE PERFORMANCE CHARACTERISTICS OF INSTANTANEOUS INDICATORS (4)

Type	Signal	Static calibration	Frequency response	Freedom from vibration	Freedom from temp	Freedom from electric noise	Reliability
Variable resistance (catenary type)	Pressure	Yes	Good	Good	Good	Good	Good
Variable capacitance (carrier type)	Pressure	Yes	Fair	Fair	Poor	Good	Good
Photoelectric	Pressure	Yes	Fair	Poor	Fair	Poor	?
Piezoelectric	Pressure	No	Fair	Poor	Poor	Poor	Fair
Magnetic (carrier)	Pressure	Yes	Poor	Fair	Poor	Fair	?
Magnetic reluctance	dp/dt	No	Fair	Poor	Fair	Good	Good
Magnetostrictive	dp/dt	No	Fair	Poor	Fair	Good	Good

There are very many possible methods of generating signals proportional to small displacements. There are, however, only three practical methods at present that possess both good high frequency response and high temperature stability. These are: (*a*) The quartz crystal, piezoelectric displacement pickup. (*b*) The temperature compensated strain-gage pickup. (*c*) The variable capacitance displacement pickup.

Pressure receivers that utilize these three types of signal generating systems are commercially available. McCullough (4) has made a survey of the relative merits of these commercially available instruments; this survey is summarized in Table 1. In this survey, the strain-gage catenary diaphragm appears to have the best performance of all the instruments tested. The excellent performance of this instrument is largely due to the use of the catenary diaphragm. It is, however, entirely possible to construct a catenary diaphragm pressure receiver utilizing either a piezoelectric or a variable capacitance-type signal generating system that will produce the same high performance as the strain-gage system. The strain-gage system, however, has the advantage of being quite simple in construction and generally reliable. The quartz crystal has the advantage of possessing a very high natural frequency, making possible measurements up to 1 million cps. Such piezoelectric crystals have unequaled supremacy in the very high frequency domain.

The simplicity and flexibility of signal generating systems which employ resistance variations, in which class the strain gage belongs, are derived mainly from the fact that either d-c or a-c excitation may be used. The frequency ranges of seven possible methods of realizing a signal from a strain gage are shown in Fig. 7. In general, the more narrow the frequency band to be measured, the simpler is the system required for the measurement. Quite often, when a wide band of frequencies is to be measured, it is simpler to use two systems—one to cover the upper, and one to cover the lower half of the band—than to use one system to cover the whole band. However, from the point of view of the operator, it is more expedient to use one system, wherever possible, to cover the complete frequency range required. A more detailed description of these various systems appears in the references cited in Fig. 7.

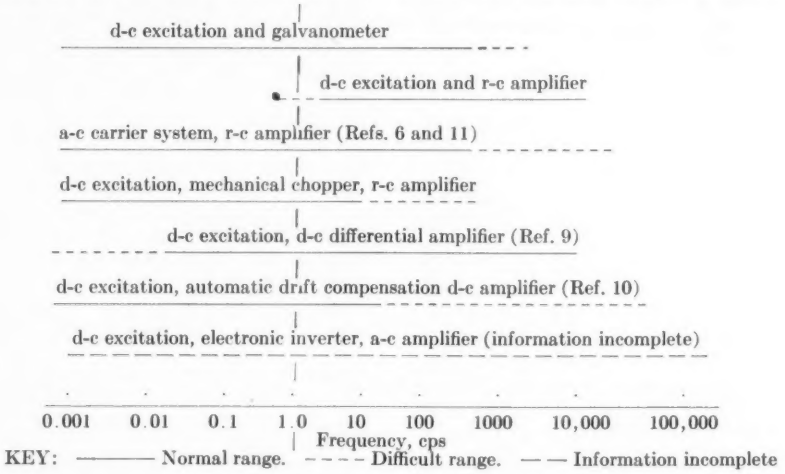

d-c excitation and galvanometer
d-c excitation and r-c amplifier
a-c carrier system, r-c amplifier (Refs. 6 and 11)
d-c excitation, mechanical chopper, r-c amplifier
d-c excitation, d-c differential amplifier (Ref. 9)
d-c excitation, automatic drift compensation d-c amplifier (Ref. 10)
d-c excitation, electronic inverter, a-c amplifier (information incomplete)
0.001
0.01
0.1
1.0
10
100
1000
10,000
100,000
Frequency, cps
KEY: ——— Normal range. - - - - Difficult range. — — Information incomplete

FIG. 7. FREQUENCY RANGE OF METHODS USED TO REALIZE A SIGNAL FROM A STRAIN-GAGE PRESSURE RECEIVER

Conclusions

Pressure receivers to be used in rocket research must be able to dissipate heat at the rate of 10 Btu per sq in. per sec. The natural frequency of this pressure receiver must be higher than 10,000 cps. Furthermore, the pressure signal derived therefrom, must be relatively insensitive to temperature fluctuations.

The water-cooled catenary diaphragm pressure receiver, described herein, meets these specifications more closely than other types tested. Development of this type of pressure receiver is still under way; it is hoped that reliable pressure measurement in rocket research will be possible in the near future, under all operating conditions.

Acknowledgment

The author wishes to express his gratitude to Dr. Frederick Liu and his colleagues at the Forrestal Research Center, Princeton University, for their invaluable assistance in the development of the water-cooled catenary diaphragm pressure indicator, and to Mr. Philip A. Lapp of the Massachusetts Institute of Technology for his efforts in connection with the preparation of this paper.

References

1 "Aspects of Combustion Stability in Liquid Propellant Rocket Motors, Parts I and II," by L. Crocco, JOURNAL OF THE AMERICAN ROCKET SOCIETY, vol. 21, November 1951, pp. 163–177; vol. 22, January-February 1952, pp. 7–16.

(*Continued on page 145*)

Methods of Measuring Thrust[1]

JAMES A. BIERLEIN[2] and KARL SCHELLER[2]

Wright Air Development Center, Dayton, Ohio

The thrust of rockets may be measured either by direct or by inferential methods. The principles of various procedures in each category are reviewed, and the characteristics and equipment associated with each technique are described briefly. Consideration is given to the problem of measuring varying as well as steady-state thrusts. The component elements of thrust stands are discussed and their areas of utility are indicated.

Introduction

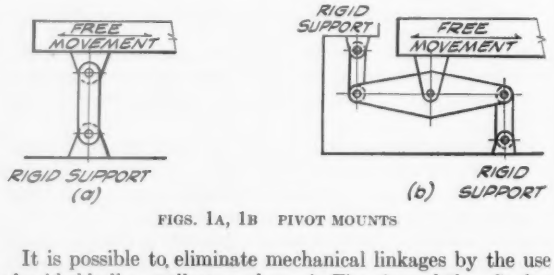
The testing of rockets, as opposed to reciprocating engines, presents to the experimenter the problem of measuring force rather than shaft power. The measurement of the thrust force may be accomplished by direct methods in which the force is transmitted to an instrument designed to respond to this specific stimulus; or it may be done by indirect procedures involving measurement of one or more properties of the system which can be related to the thrust. Both methods utilize equipment and techniques which have roots in the general body of engineering practice, and more particularly comprise adaptations of procedures developed for reciprocating-engine testing. It is the purpose of this review to discuss the relatively few instruments and procedures that have proved satisfactory for thrust measurement.

Engine Mounts

The direct measurement of thrust requires that the force applied to the measuring instrument be exactly equal to the thrust produced by the rocket or that it be related to the thrust in a definite way. Any friction or other force which restrains movement of the engine mount in an unpredictable fashion imposes upon the inherent errors of the measuring instrument an additional uncertainty which cannot be calibrated out. Therefore it is always necessary to provide for an engine under test a mount which will contribute transmission errors no larger than those associated with the measuring instrument itself; the use of a fine force instrument will not secure high accuracy if the thrust stand is crudely made or improperly selected for its purpose.

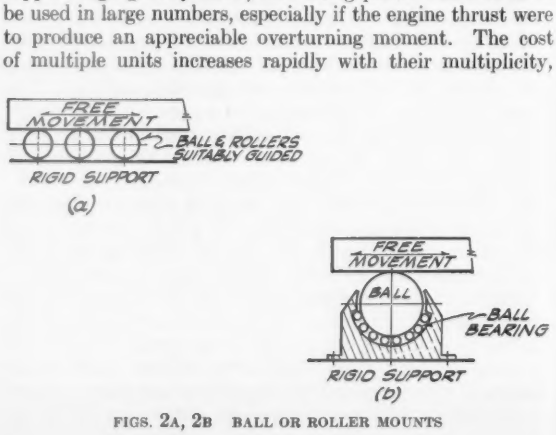
The ideal engine mount would offer no resistance to movement, and this movement itself would introduce no forces extraneous to the thrust which could affect the measuring instrument; consequently the mount could be allowed to move through an indefinite distance to accommodate the instrument. In practice, it is desirable to minimize all movement, in order to suppress the generation (and spurious recording as thrust) of inertia forces at start-up, shutdown, and other times when the thrust is changing rapidly. Hence most measuring instruments, as will be seen, are designed to approximate a zero deflection; a strain of 0.005 in. at full rated load is typical. Therefore it is sufficient in the practical design of engine mounts if the ideal criteria are closely approached for the case of small movement.

Figs. 1a and 1b show a support utilizing the pivot points which are made as free from friction as possible by means of ball or roller bearings, trunnions, or knife edges. This scheme is the basis of so-called parallelogram mounts, in which multiple units of type 1a are used to support the engine on a horizontal bed; an obvious variant is the pendulum mount, in which the bed is suspended from above. The movement of such mounts introduces a horizontal force due to the action of gravity, which can be calibrated out; the associated vertical movement, tending to wipe the mount across the thrust pickup instrument, may produce troublesome secondary forces within the instrument. This vertical movement can be eliminated by use of scheme 1b, a distinct improvement which seems not to be widely appreciated. In general, parallelogram or pendulum mounts are characterized by high friction because a minimum of eight pivot points is usually required, and the number may be much greater if (say) four units of type 1b are used to support a rectangular bed. However, this kind of mount is simple and rugged, and the horizontal bed is convenient and adaptable to the support of tankage as well as thrust chambers. The preferred range of use is for thrusts between a few hundred and and few thousand pounds. For very small engines, the necessary weight of a commensurate mount in itself creates bearing frictions that may be large compared to the thrust; for very large thrusts, the high engine weight tends to produce the same effect.



FIGS. 1A, 1B PIVOT MOUNTS

It is possible to eliminate mechanical linkages by the use of guided balls or rollers, as shown in Figs. 2a and 2b. Such a rolling mount is excellent from the standpoint of friction, but it is practical only for supporting small weights. To support high gravity loads, the rolling pieces would have to be used in large numbers, especially if the engine thrust were to produce an appreciable overturning moment. The cost of multiple units increases rapidly with their multiplicity,



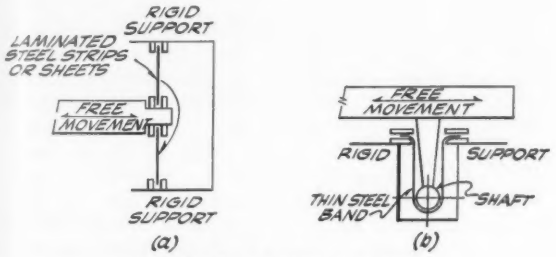
FIGS. 2A, 2B BALL OR ROLLER MOUNTS

[1] The opinions expressed are those of the authors and are not to be construed as the official views of the Air Force with respect to the merits of any equipment or procedures described.

[2] Research Engineer, Flight Research Laboratory.

on account of the close machining tolerances required to assure uniform distribution of the load. This type of mount is therefore most suitable in the small-thrust regime, and it probably deserves more widespread usage than it has received, especially for propellant testing and similar research below the 1000-lb thrust level. The rolling element shown in Fig. 2b is particularly ingenious, since it minimizes the friction which must inevitably accompany the guidance of the primary ball. It is produced commercially by the Matthew Conveyor Company, primarily for the shop handling of heavy-gage sheet metal. The largest size manufactured (3-in. ball diam) is rated to support a 650-lb load.

Figs. 3a and 3b show one version of the flexural or elastic hinge type of mount. Although such supports offer a resistance to movement, they are frictionless in the sense that the resisting force is almost wholly dependent upon the elastic qualities of the hinge and consequently varies according to a definite physical relation, provided the hinge stresses are within the elastic limit. Flexural supports are simple to construct and maintain. The type shown in Fig. 3a can be used to mount rockets with the thrust axis oriented vertically—a feature which is often important in missile development work.



FIGS. 3A, 3B FLEXURAL MOUNTS

The bell crank (Fig. 4) is useful both as a primary mount and as a force-transmitting link in conjunction with the foregoing mounts. Its value as a transmitting link is due to the magnification or reduction of the force which can be achieved to adapt the engine thrust to the capacity of the particular measuring instrument available. As a primary mount, it can be used to secure any desired orientation of the engine; further, the single hinge helps to minimize friction. One disadvantage is that the instantaneous weight of the rocket and of the crank arms is transmitted to the measuring instrument as thrust, and correction must be made for this in interpreting the record. In testing a thrust chamber alone, it is possible to supply propellant through flexible lines and calibrate out the chamber and arm weight by taking a baseline thrust reading before start-up; in the case of mounting complete missiles or engines with integral propellant tankage, it is necessary, in addition, to measure the decrease in weight with time (e.g., by integrating flowmeters). The bell crank mount is widely used in measuring small thrusts—below 200 or 300 lb—in propellant evaluation work using nonintegral tankage. It is also a very common mount or link element for measuring thrusts above 10,000 lb.

Rocket missiles intended for vertical operation and test are frequently attached directly to the measuring instrument, which supports the whole weight of the missile when it is not firing. When this technique is used, care must be taken to superimpose the thrust vector upon the symmetry axis of the force instrument. Ordinarily it is sufficient to assume that the thrust axis of the rocket coincides with the geometric axis of the nozzle, the angular discrepancy between the two is rarely as large as one degree, and this amount of jet misalignment contributes negligible error to the measurement of the magnitude of the thrust. It is always advisable to provide sway bracing, which may take the form of rigidly mounted rollers bearing radially on pads located at three or more points around the periphery of the missile. By incorporation of thrust instruments in the sway braces, it is possible to determine side forces and estimate the amount of jet misalignment—a rather specialized problem, but one which has occasional practical importance and on which some work has been done.

Direct Measurements

There are a variety of instruments available commercially for measuring directly the thrust produced by a jet engine. These instruments may be grouped into four general categories: mechanical, pneumatic, hydraulic, and electrical. Each of these will be discussed in turn, indicating the ranges, accuracy, and limitations of the various types of instruments, and the names of their manufacturers.

Mechanical Systems

Mechanical thrust measuring systems are essentially scales in which the engine thrust is reduced by a linkage of bell cranks, lever arms, and frictionless fulcrums to a force small enough to move a pointer over a dial. The bell crank fulcrums, which are the most heavily loaded, would probably be of the elastic hinge or trunnion type, while knife edges would be satisfactory for the other fulcrums. The Yale and Towne Manufacturing Company (successor to the former Krone Scale Company) offers a mechanical scale system for thrust measurements over a range from 500 to 28,000 lb of thrust. It claims an accuracy of 1 per cent of the scale reading over the entire thrust range through the incremental use of a 4000-lb dial with 5-lb divisions. Federal specifications for commercial scales require that they be accurate to 0.1 per cent of the full range of scale or to the nearest dial division, whichever is smaller. Hence, over the range from zero to 4000 lb, the allowable error for any reading would be ±4 lb. By adding a drop weight to the linkage system, the next increment of thrust range, from 4000 to 8000 lb is covered on the same dial with an allowable error of ±8 lb. The capacity of the scale is increased in increments of 4000 lb by the addition of successive drop weights until the entire range is covered. For any reading over 400 lb, the scale error would be less than ±1 per cent of the force delivered to it.

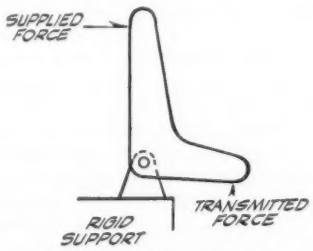


FIG. 4 BELL CRANK MOUNT

The system just described can be refined by adding the drop weights automatically and by transmitting the dial readings to remote control locations to be read visually or to be automatically recorded. The cost of this type of scale installation is dependent upon the accuracy and degree of refinement desired.

Mechanical scale weighing systems may be obtained from the Toledo Scale Company as well as from Yale and Towne. They have been used extensively for dynamometer test stands but are not widely employed for rocket thrust measurements because of their excessive size, mechanical complexity, and slow response.

Pneumatic Cells

The Hagan Corporation, Pittsburgh, Pa., manufactures an air-operated force measuring cell known as the Hagan "Thrustorq." The instrument consists in essence of a dia-

phragm, an air chamber, and a poppet valve. A force applied to one side of the diaphragm is balanced by air pressure on the other side. When the applied force is not equal to the balance pressure, the diaphragm moves from the null position, permitting the poppet valve to exhaust or admit air until the null diaphragm position is again attained under the new balance air pressure. The change in air pressure is proportional to the thrust. With proper calibration the thrust can be read on a Bourdon gage or on a manometer. The deflection necessary to operate the poppet valve is 0.002 in. The cell is intrinsically self-compensating for temperature changes. It is furnished with a viscous damper to maintain stability and to allow for reading pulsating loads.

The manufacturers claim an accuracy for the cell of one part in 3000. When the Thrustorq is used in conjunction with a Bourdon gage, external pressure variations must be compensated. This may be accomplished by piping air from the vicinity of the force cell to a small cylinder and piston arrangement in the gage. When the pressure changes in the immediate environment of the cell, a compensating force is exterted on the Bourdon tube to correct its zero thrust reading. When manometers are used for thrust indications, the accuracy of the measurements depends upon the manometer liquid, the lighter fluids yielding more accurate readings at the expense of greater manometer lengths. In this usage, external pressure changes at the cell may be automatically compensated for by piping the open end of the manometer tube back to the cell environment.

The largest Thrustorq produced commercially measures up to 11,600 lb with an air supply pressure of 100 psia. This capacity can be increased slightly by either increasing the supply balance pressure or reducing the load through a lever system.

Instruments of this type have been used for a number of years for rocket testing, but in many laboratories the present trend is to use electrical gages, to be described shortly, primarily because of their more rapid response and ability to follow dynamic loads. Alignment difficulties have also been experienced with these cells, and some users have had to use special linkages to transmit the force to the cell.

Hydraulic Cells

The measurement of thrust by hydraulic means enjoys a time-honored place in early rocket development history. The first rocket test stands built in this country employed homemade hydraulic jacks of various types and origins for thrust measurements. The thrust force actuated a piston moving in a cylinder filled with hydraulic fluid. The increased pressure of the fluid was transmitted directly to a Bourdon gage through a line connected to the cylinder. The thrust force was given by the product of the observed pressure and the known piston area. These installations usually possessed a high degree of viscous damping and excessive mechanical friction. Hydraulic force measuring capsules are now available from a number of commercial manufacturers and have been used successfully on torque and thrust stands.

The A. H. Emory Corporation of New Canaan, Conn., makes a hydraulic force cell comprising a cylinder, a small oil space, a diaphragm, and a piston firmly attached to the cylinder by means of an elastic ring. A thrust force on the piston is transmitted to the oil through the diaphragm, producing an oil pressure directly proportional to the thrust. This pressure is transmitted through a hydraulic line to a Bourdon type gage which is calibrated to read in terms of pounds of thrust experienced by the piston of the force cell. Preloading springs are incorporated in the unit to produce an initial oil pressure at zero thrust of about 30 psia. The total deflection of the engine mounting under capacity thrust is somewhat less than 0.005 in.

Since the oil is virtually incompressible, it is used in a closed system, and a change in temperature changes the oil pressure, producing an error in thrust reading. For sufficiently large temperature variations, an automatic compensating device may be used. This consists of a small capsule of the oil used in the primary measuring circuit, placed in the vicinity of the force cell and piped to a small cylinder in the gage. When a change in the volume of oil is produced through a temperature change, a compensating force is exerted on the Bourdon tube through a properly selected spring. External pressure variations are compensated for in the manner described previously for the Hagan Thrustorq.

Hydraulic force cells are also manufactured by the Young Testing Machine Company at Bryn Mawr, Pa. These are similar in design and principle to the Emory hydraulic capsule.

The accuracy of hydraulic force cells depends primarily upon the accuracy of the gage used to indicate the thrust. The guaranteed accuracy of any one gage is 0.1 per cent of its capacity at any point within its range. A desired degree of accuracy may be attained by using different gages for various ranges. For example, if it is desired to limit the allowable error to 1 per cent over a thrust range of 500 to 20,000 lb, two gages would be required; one to cover the range from 500 to 5000 lb, and the other to cover the range from 5000 to 20,000 lb.

Hydraulic thrust cells are subject to the same limitations as the pneumatic type, namely, low response and misalignment difficulties. Furthermore, the dependability of their pressure and temperature compensating devices is open to doubt until they are thoroughly tested.

Electrical Cells

Electrical thrust-measuring devices depend for their operation upon the strain of a solid load-carrying element which in turn causes a change in the electrical properties of an indicating element. In some cases (for small forces) the load-carrying element is also the indicating element.

The Baldwin-Lima-Hamilton Corporation manufactures a force cell which utilizes their well-known SR-4 strain gage. The sensitive element is a rectangular steel column, to the sides of which are bonded specially designed forms of the strain gage. A cut-away view of the cell is shown in Fig. 5.

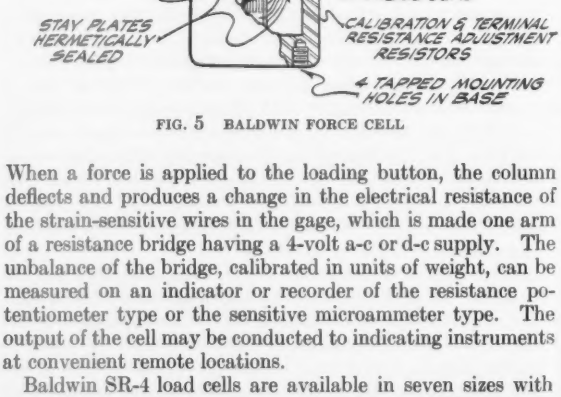

LOADING BUTTON
10 FT. NEOPRENE COVERED SHIELDED CABLE
BAKELITE STRAIN GAGES ON LOAD SENSITIVE COLUMN
CABLE SEAL
STAY PLATES HERMETICALLY SEALED
CALIBRATION & TERMINAL RESISTANCE ADJUSTMENT RESISTORS
4 TAPPED MOUNTING HOLES IN BASE

FIG. 5 BALDWIN FORCE CELL

When a force is applied to the loading button, the column deflects and produces a change in the electrical resistance of the strain-sensitive wires in the gage, which is made one arm of a resistance bridge having a 4-volt a-c or d-c supply. The unbalance of the bridge, calibrated in units of weight, can be measured on an indicator or recorder of the resistance potentiometer type or the sensitive microammeter type. The output of the cell may be conducted to indicating instruments at convenient remote locations.

Baldwin SR-4 load cells are available in seven sizes with maximum capacities of 2000, 5000, 10,000, 20,000, 50,000, 100,000, and 200,000 lb, respectively. Their popular Type "C" cell is a compression unit only; however, they now produce force cells that may be used either in tension or compression. Baldwin will also provide cells in special capacities and for high temperature and corrosive atmosphere work. Temperature compensation is built into all of their cells to minimize the effects of temperature upon zero reading and

sensitivity. Thrust measurements may be made with a single cell or obtained through several cells as desired. In the latter case, the response of the whole group of cells may be automatically totalized to give a single reading.

The error of the standard force cell is specified by the manufacturer to be not more than 0.25 per cent of capacity output at any point in its range. Special cells calibrated by the National Bureau of Standards can be had at additional cost; these have a maximum error of 0.1 per cent of capacity output at any load. The response of the cell is linear within the above-cited limits for static loads. The response to instantaneous loads is rapid, although, as with most force cells, no positive statement may be made concerning the linearity; under the usual installation conditions, the cell will resolve frequencies up to 500 cps, which is probably better than the thrust-stand response in most cases. The output of the Baldwin cell is about 10 millivolt at full load. This low output necessitates the use of rather sensitive recorders, especially for d-c outputs; a-c outputs can be amplified to accommodate the recording apparatus.

There are many types of measuring and recording instruments that can be used with the cell. The Brown Instrument Division of the Minneapolis-Honeywell Corporation at Philadelphia, Pa., has developed an instrument in conjunction with Baldwin for use with the SR-4 gage. It is an adaptation of the Brown precision indicator used for thermocouple work, an automatic instrument of extended range providing 2000 reading divisions. The accuracy of the instrument may be expected to be within $^1/_2$ per cent of the scale reading down to 0.1 per cent of the rated capacity of the thrust measuring system. With such a system, the error in thrust reading should not exceed 1 per cent down to a thrust of 1000 lb. For lower thrust values, the errors will increase, exceeding 5 per cent at a thrust of 100 lb.

The Allegany Ballistics Laboratory (1)[2] has developed an inverter to increase the output of this and similar type strain gages. The output of the Baldwin cell is used to modulate the amplitude of a 50-kc carrier wave from the inverter. The latter consists of a modified Hartley oscillator circuit used to generate a carrier frequency of 50 kc, a modulator circuit, and two 6AU6 tubes in conventional resistance-coupled amplifier circuits. The electronic inverter is marketed commercially by the Allegany Instrument Company as its d-c bridge and amplifier. Allegany Instrument also manufactures an elaborate instrument assembly embodying as components four d-c bridge and amplifiers, eight automatic calibrators for 1- and 2-arm gages and 4-arm bridge-type pickups (like the Baldwin), two dual-beam oscillographs, a drum camera, a control unit, a synchronizing unit, and a time standard. Designated as a dynamic temperature and strain recorder, it is intended to furnish complete equipment for measuring strains, as well as temperature, which does not concern us here.

Statham Laboratories, Inc., of Los Angeles, produces a so-called dynamometer for the measurement of thrust in ranges of 25 lb to a maximum of 50 lb. The load may be applied in either tension or compression. The sensitive element of the dynamometer is an unbonded strain gage in the form of a completely balanced bridge of strain-sensitive resistance wire. Statham claims that this transducer is accurate, stable, and linear. An accuracy and linearity of $^1/_2$ per cent of capacity of the gage are specified. The effect of temperature on the zero point and sensitivity is stated to be not greater than 0.01 per cent per °F. The output voltage of the dynamometer may range from 10 to 175 millivolt; hence it may be expected to be somewhat easier to measure and less susceptible to line losses than is the case for the Baldwin force cell. It may be used in conjunction with the Allegany Ballistics Laboratory system to increase the magnitude of its output and frequency of response. By virtue of its unbonded construction, the Statham dynamometer is limited to low thrusts, unless force-reduction linkage is employed.

The Wiancko Engineering Corporation of Altadena, Calif., manufactures force pickups operating upon a stress ring principle. The electrical element of the pickup consists of two inductance coils mounted on a core with two air gaps within a hardened steel stress ring. As the ring is compressed or extended under the action of a thrust load, the length of one gap is increased and the other is decreased by the movement of a lightweight armature connected directly to the ring. No push rods or other linkages are used. A special internal mounting arrangement is employed for the magnetic core and armature, which results in a relative motion twice as great as that of the external connections.

The inductance coils are connected as two arms of a Wheatstone-type bridge. The output of the bridge, when unbalanced, drives a discriminator-type coupling unit, incorporating a germanium crystal ring demodulator. A carrier oscillator supplies the excitation voltage for the pickups and the bias current for the discriminator. The oscillator supplies 20 volts at 3000 cps to the pickup units, giving them a frequency response to dynamic loads of 500 cps. A relatively large output is obtained from the pickup without amplification, resulting in greatly increased stability and precision of the over-all recording system. The output is sufficient to actuate a galvanometer-type recorder directly.

The manufacturers state that their system does not require a significant stabilization time to reach the proper reading, claiming an over-all time constant of less than 0.5 millisec, plus the time constant of the recorder. The maximum drift and hysteresis error is guaranteed to be less than 1 per cent under dynamic as well as static conditions. Distortions due to eccentric loading, shear and bending forces are balanced out at the point of measurement by virtue of the design of the stress ring. The maximum over-all error, under dynamic or static conditions, is guaranteed to be less than 0.5 per cent of the thrust being measured, or 0.1 per cent of the full scale reading of the pickup, whichever is larger.

The Wiancko type 3FA force pickup is available in a great variety of sizes, rated at 1 lb to 100,000 lb working range. A temperature correction should be applied to the sensitivity factor at the rate of 1 per cent per 50 F due to the change in modulus of elasticity of the stress ring with temperature.

Indirect Measurements

Several methods exist whereby thrust can be evaluated without a direct force measurement. The accuracy of these indirect methods runs the gamut from good to highly approximate, and the requirements of the work at hand must determine whether one of them may be suitable for use.

For many purposes, it suffices simply to measure the chamber pressure and the throat area of the rocket, and then to apply the isentropic thrust coefficient value (2) appropriate to the nozzle area ratio and the atmospheric pressure involved. A specific heat ratio of 1.25 or 1.30 may be assumed for most rocket exhaust gases in evaluating the thrust coefficient, which is relatively insensitive to the exact value used. Thrust values determined in this way usually lie within 5 per cent of the "true" value, as measured directly. The accuracy is determined not only by the pressure and area measurements (and the throat area changes during operation because of thermal expansion); it is also affected by the extent to which the actual nozzle expansion process deviates from the idealized assumptions from which the theoretical thrust coefficient is derived. In general, this deviation is small for nozzles of customary divergence angle operating under conditions of correct, or nearly correct, expansion. If shock or separation phenomena occur within the nozzle, the isentropic thrust coefficient is no longer applicable, and serious errors may arise from its use. Green (3) has proposed some practical guides for determining the limits of applicability of the thrust coefficient.

[2] Numbers in parentheses refer to the References on page 132.

It is also possible to measure the thrust of a rocket by static pressure integration over the whole interior surface of the combustion chamber and nozzle. This procedure can be made as accurate as the experimenter desires—within the limitations of the pressure gages used—by increasing the number of points at which the pressure is measured. The method involves no assumptions concerning the thermodynamic character of the flow, and the presence of shock or separation phenomena in the nozzle is not an impediment. The instrumenting of a rocket for this kind of measurement is laborious, and the reduction of the data is tedious. Further, this method is suited only to development purposes and not to routine test, since holes must be bored through the chamber and nozzle walls. For these reasons, pressure integration does not appear to have received serious consideration for practical thrust measurement, and no significant background of experience has been accumulated. However, it appears to the authors that pressure integration has unique advantages for the measurement of transient thrusts and the resolution of high-frequency ripple in the nominal steady state. The limitation to frequency response in direct thrust measurement is usually imposed by the engine and its supporting mount, rather than by the instrument itself. This limitation is virtually impossible to overcome, since the mass, elasticity, and damping properties of the engine-and-mount combination are automatically restricted by other considerations to certain maximal or minimal values. In the measurement of gas pressure, however, the full response of the measuring instrument can be utilized. A time history of pressures, referred to a common time base, can be made to yield correspondingly good resolution of thrust variations. The characteristics of fast-response pressure pickups are described elsewhere in this issue (see paper by Y. T. Li, pp. 124–127).

Bundy, Strong, and Gregg (4) have used an optical method to measure the velocity of rocket exhaust gases. In principle, this information can be used to deduce the thrust if a simultaneous measurement of the mass consumption rate of the propellant is available; if the exhaust gas is not correctly expanded, the thrust estimated as the product of mass flow and velocity must be corrected by addition of a pressure-thrust term. Bundy et al. measured the gas velocity by an interferometric determination of the Doppler shift of the wave lengths of spectral lines emitted by traces of sodium or lithium introduced into the gas for this purpose. The exhaust pressure, necessary to apply the pressure thrust correction, can also be estimated with the same equipment. The original publication must be consulted for a detailed account of the technique. Inasmuch as the Doppler effect is small for velocities of rocket-exhaust magnitude, exceptionally careful work is required to achieve results of even a moderate accuracy. In the present state of development, the uncertainty associated with a single velocity measurement is about ±500 ft/sec, representing a possible error of 5 to 10 per cent relative to ordinary exhaust velocities. Hence it is to be expected that the method would find application only in very special circumstances.

Altman (5) has suggested that thrust can be estimated from the wave length of the pattern of standing shock diamonds visible in luminous exhausts. Applying a two-dimensional theory of Prandtl (6), he finds that the wave length λ (in.) and the thrust F (lb) are related by

$$\lambda^2 = \frac{6.823}{\sqrt{\gamma p_0}} \left[1 - \frac{1}{M^2}\right] F \quad [1]$$

where M is the Mach number, γ the specific heat ratio, and p_0 the atmospheric pressure in psi. The coefficient of F is insensitive to the value of M, and for a typical Mach number of 2.5 and standard atmospheric pressure, the thrust is given by

$$F = 9.2\lambda^2 \quad [2]$$

Altman found experimentally that this formula predicts thrusts in the 50-lb range with a maximum error of 5 per cent over a wide range of chamber pressures (or exhaust Mach numbers). It also yields a correct value of about 48,000 lb for the take-off thrust of the German V-2 missile.

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Methods of Flow Measurement

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All flowmeters may be placed in one of three basic classifications: the differential pressure type, the volumetric type, and the mass rate type.

Differential pressure flowmeters incorporate a suitable restriction in the flow passage. For steady-state liquid flows, the pressure drop caused by the restriction is related by a simple square law to the velocity, so that when either the pressure difference or the area of the restriction is fixed, the value of the other parameter will provide an indication of the volumetric flow rate. For known fluid density, the mass flow may then be computed. This type of flowmeter is not generally suited to the measurement of pulsating flows, since the square-law relationship means that, if any averaging action occurs in the pressure measurement, an erroneous signal will be obtained.

Volumetric flowmeters are distinguished from the differential type in that they measure fluid velocity independently of pressure. Although inherently more accurate than the differential type due to the relatively small effect of viscosity, they possess the disadvantage of requiring a knowledge of fluid density in order to obtain mass flow. Turbine meters and electromagnetic flowmeters, which can be used in pulsating flows, are some specific examples of this class. The use of the hot-wire anemometer for the measurement of liquid flows is also discussed.

In the case of the true mass rate flowmeter, the signal is directly proportional to the mass flow itself. Although several designs of a mass flowmeter have been conceived, only one appears to be commercially available at this time. Its operation depends on the measurement of the angular momentum of a rotating fluid passage.

Introduction

THE measurement of flow is of vital importance in all phases of jet propulsion research. In a great many cases a knowledge of average or steady-state flow rates is sufficient, and the problem of measuring this type of flow has been successfully solved for nearly every conceivable type of application. However, in recent years the problem of detecting instantaneous values of the flow rate in a time-dependent system has become of greater importance in the jet propulsion industry. The study of such critical high-frequency phenomena as combustion instability, fuel control response rates, pump characteristics, etc., would be greatly simplified if accurate measurement of instantaneous flow rates were possible.

This paper presents a brief review of the common methods of measuring average or steady-state flows, and then proceeds to a somewhat more detailed discussion of the available types of instantaneous flowmeters. The discussion will, in general, be limited to flow measurements in liquid systems.

Steady-State Flow

The measurement of steady-state liquid flow rates has been accomplished in a number of different ways. The most commonly used method involves a group of flowmeters which depend for their operation on the relationship between flow and pressure as given by the familiar Bernoulli equation

$$P + \frac{\rho U^2}{2} = \text{const} = P_0$$

where

P_0 = total or stagnation pressure
P = static pressure
ρ = fluid density (assumed constant for liquids)
U = flow velocity

To determine the mass flow, we can derive directly from this the "orifice" equation, since

$$U_t = \sqrt{\frac{2(P_0 - P)}{\rho}}$$

where U_t = flow velocity at vena contracta, which is large compared with the velocity upstream of the orifice and the mass flow is given directly by

$$m = A_t C \sqrt{2\rho(\Delta P)} \quad \ldots\ldots\ldots\ldots\ldots [1]$$

where

m = mass flow rate
A_t = orifice area
C = orifice discharge coefficient
ΔP = pressure drop between an upstream point and the vena contracta
ρ = fluid density (assumed constant)

Thus, for constant density fluids, the mass flow through a constriction is directly proportional to the square root of a characteristic pressure drop. A large class of flowmeters consists, then, of a mechanism for accelerating the flow and a device for measuring the pressure drop thus created. The actual relationship between flow and pressure is almost always determined empirically for any given flowmeter at the conditions under which it must operate, since the discharge coefficient C cannot otherwise be accurately defined.

The most commonly used flowmeter of this type is the simple orifice (Fig. 1). Its advantages are economy, ease of in-

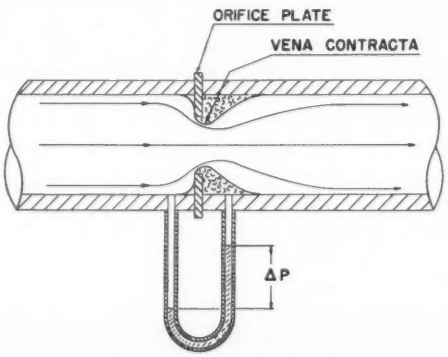

FIG. 1 SIMPLE ORIFICE METER

[1] Research Associate. Member ARS.

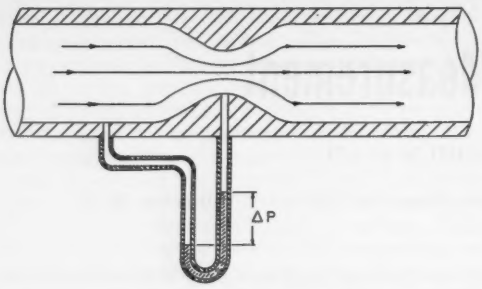

FIG. 2 VENTURI METER

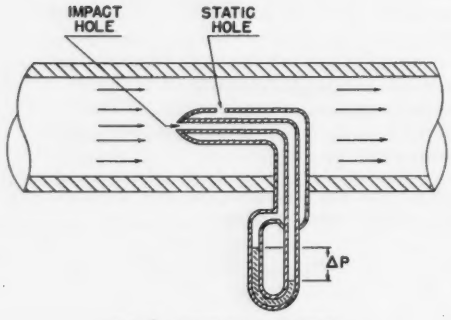

FIG. 3 SIMPLE PITOT TUBE

stallation and replacement, and moderately good accuracy. Further, it may be used for gases or wet vapors as well as for liquids, although it must, of course, be recalibrated for application to different fluids. Its primary disadvantage is the introduction of a stagnation pressure drop which may be appreciable at high flow rates, and its sensitivity (which depends on the magnitude of the static pressure drop) is consequently limited. The linear range is also rather small because of the change in discharge coefficient with flow rate. Furthermore, it can be used only when the undisturbed fluid velocity is negligible compared to the velocity of the vena contracta. Further details may be found in (1)[2] and (2).

The Venturi flowmeter (Fig. 2) eliminates some of the disadvantages of the orifice plate by providing a gradual change in cross-section area, thus reducing the intensity of turbulence and decreasing the stagnation pressure loss developed by the simple orifice. The Venturi may thus be used for much higher flow rates, and has the further advantage of maintaining a more nearly constant discharge coefficient, which extends its linear range.

The ordinary Pitot tube (Fig. 3) obeys the same pressure-velocity relation as the orifice and the Venturi, but differs from these instruments in that it can be used with reasonable accuracy only when the undisturbed fluid velocity is not negligible. The Pitot-Venturi (Fig. 4) is a combination of the Venturi and the simple Pitot tube, and is perhaps the most accurate of this class of flowmeters over the widest range, since it can produce the highest static pressure drop for a given flow rate without an excessive loss in stagnation pressure (3, 4).

The Pitot and Pitot-Venturi flowmeters are particularly applicable to the measurement of compressible fluid flow rates, in which the undisturbed velocity is usually appreciable. However, it must be remembered that both the Pitot tube and Pitot-Venturi actually measure velocity, and not mass flow. Hence, although it is usually quite simple to relate mass flow and velocity in an incompressible fluid, the variation of density of a compressible fluid makes this conversion more complicated in that additional pressure and/or temperature measurements must be made, and the relationship between pressure, temperature, and density (e.g., Boyle's law for perfect gases) must be known. Further, a correction must be introduced for the effect of the velocity profile in a particular duct.

A number of instruments are available for detection of the pressure drop induced by these flow sensing elements. The most common are the simple mercury or water manometer, the mercury float, the metal bellows, strain gages, and other types of differential pressure transducers. Commercial display instruments are generally calibrated to read flow rate directly. Several different types are available; e.g., direct-reading indicator similar to an ordinary pressure gage (Barton), pen recorder (Taylor, Foxboro), differential pressure transducer (Foxboro, Flader, Statham, Baldwin, Trans-Sonics, etc.) in conjunction with recording potentiometer, oscilloscope, or oscillograph.

All the afore-mentioned flow sensing elements are based fundamentally on the characteristics of a fixed orifice. Another class of differential flowmeters uses a variable orifice to supply an indication of fluid flow rates. The basic operating principle of this instrument (Fig. 5) differs from the fixed orifice with its constant flow area and varying pressure drop in that the flow area is variable and the pressure drop constant. This is done by using a float in a tapered tube, and, since the net weight of the float is the same regardless of its elevation, it follows that the pressure drop across the float must be constant. Thus, as the flow increases, the float moves up the tapered tube, and the flow by-pass area around the float increases until the pressure drop falls to a value which just balances the weight of the float.

For an incompressible fluid, the pressure drop across the float is given by

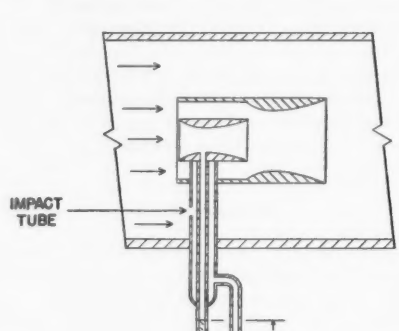

FIG. 4 PITOT-VENTURI METER

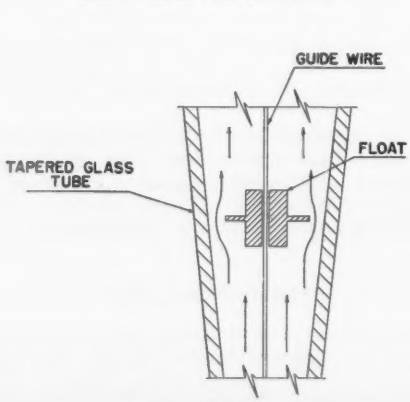

FIG. 5 ROTAMETER

[2] Numbers in parentheses refer to the References on page 140.

$$\Delta P = \frac{V_f(\rho_f - \rho)}{A_f}$$

where

V_f = volume of float
ρ_f = density of float
ρ = density of liquid
A_f = largest cross-sectional area of float

Introducing this expression into the orifice equation, Equation [1],

$$m = A_t C \sqrt{\frac{2V_f(\rho_f - \rho)\rho}{A_f}}$$

where

A_t = annular fluid passage area around the float
C = discharge coefficient of the annular orifice

The effect of viscosity is included in the discharge coefficient C. By proper design of the float, it is possible to make C essentially constant for liquids at Reynolds numbers over 500 (e.g., the Ultra-Stabl-Vis float used by Fischer and Porter), resulting in excellent reproducibility and hence an inherently accurate instrument. The variable orifice meter, in its present state of development, is one of the most accurate of the steady-state devices, having a maximum over-all error of less than $^1/_2$ per cent of full scale. Its major disadvantages are its comparatively large size, the requirement that it be mounted vertically, the difficulties involved in high pressure applications, and the fact that it cannot be used for remote measurements without reduction in accuracy. The two major manufacturers are Fischer and Porter (Flowrator) and Schutte-Koerting (Rotameter).

Up to this point, the basic types of flowmeters which depend on the orifice for their flow sensing element have been considered. Of course, there exist a multitude of variations on these fundamental devices, most of the differences appearing in the pressure drop detection method and in the display instrument, but they all depend basically on the Bernoulli principle (Equation [1]).

A recent innovation in the field of steady-state flowmeters is the turbine type, in which a freely rotating bladed rotor is suspended in the fluid passage. A small Alnico magnet mounted in the rotor induces a pulsating electric current in a pickup coil located in the housing, the number of pulses per minute being proportional to the rotor RPM. Since the volumetric flow rate through the turbine is directly proportional to the rotor speed, the output pulse frequency responds linearly to mass flow for a fluid of constant density.

Although other propeller and turbine-type meters are available—e.g., Builders-Providence Shuntflo and Propeloflo (5), for low pressures—the sensing element (Fig. 6) manufactured by the Potter Aeronautical Company of Newark, N. J., appears to be best suited to the specialized requirements of rocket and jet engine testing; in fact, it has in the past few years become one of the standard instruments in this application. The Potter meter (6) can measure flow rates from 0.05 to over 500 lb per sec of corrosive or viscous fluids, at temperatures ranging from that of liquid oxygen up to several hundred degrees and pressures up to 4000 psi, and, with slight modification, can also be used for gases. The flow passages are so designed that the rotor is pressure-balanced, permitting the sensing element to be mounted vertically as well as horizontally. Potter supplies its meters with flared tube connections conforming to MIL specifications or, for large sizes, with standard pipe flanges, so that installation is extremely simple (Fig. 7). Accuracy of the instrument is rated at better than $^1/_2$ per cent, and, most important, the turbine meter can supply this accuracy in the average liquid flow rate when the flow is pulsating (5, 6). This last feature, more than any of its other excellent characteristics, has been one of the chief reasons for the almost universal use of Potter sensing elements in rocket and ramjet testing.

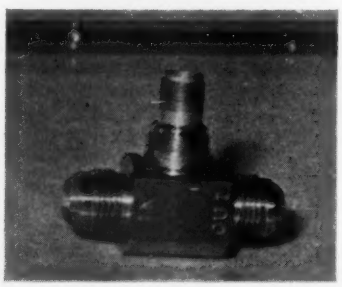

FIG. 6 POTTER FLOWMETER SENSING ELEMENT

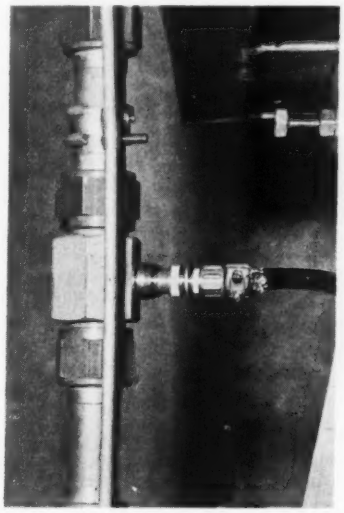

FIG. 7 VERTICAL INSTALLATION OF POTTER SENSING ELEMENT

The only apparent disadvantages of this sensing element (other than the limited frequency response, which prevents its use for instantaneous flow measurements at frequencies above a maximum of 40 or 50 cps) are the lack of overspeed protection for the rotor and the requirement that the test fluid be filtered to prevent damage of the rotor blades by solid particles. Unfortunately, overspeeding may occur rather easily in gas-pressurized liquid rocket feed systems when the propellant is exhausted and pressurizing gas passes through the meter.

Auxiliary equipment necessary for use with the Potter sensing element consists of an electronic amplifier and integrator or counter, and a recorder or other display instrument. Potter supplies an integrator-counter combination manufactured specifically for use with their sensing element, giving flow rate directly on a Brown or Leeds and Northrup recording potentiometer and, simultaneously, totalizing the flow on an electronic counter. An integrator circuit designed at the Naval Air Rocket Test Station, Lake Denmark, N. J., now in current use at Princeton in conjunction with a Leeds and Northrup recording potentiometer, shows excellent stability and linearity. Perhaps the most accurate average flow measurements can be obtained by totalization of sensing element pulses with a Berkeley high-precision electronic counter, although this instrument is usually not as convenient as one which records flow rate directly.

Another flowmeter design which is claimed to give true average flow readings in a pulsating system is described in (7). However, many operational and calibration difficulties still exist, and this meter is certainly not available for commercial use at the present time.

Instantaneous Measurements in Pulsating Flows

It is a well-known fact that when an orifice is used to measure a pulsating flow, the pressure-drop and average flow rate are no longer related by the simple orifice equation (e.g., Ref. 8). This behavior is characteristic not only of the simple orifice, but of any meter which uses Equation [1] as its basic operating principle. In order to ascertain the character of this departure from the simple Bernoulli equation, L. Crocco of Princeton has analyzed the nonsteady flow through an orifice.

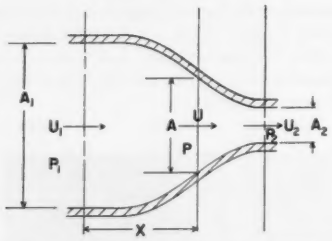

FIG. 8 SCHEMATIC FOR DYNAMIC PRESSURE-FLOW RELATIONSHIP

Consider the orifice shown in Fig. 8. For an incompressible fluid, the one-dimensional momentum equation may be written

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -\frac{1}{\rho}\frac{\partial P}{\partial x} \quad \ldots\ldots\ldots\ldots\ldots [2]$$

The instantaneous values u and P of velocity and pressure, respectively, are given by

$$u = \bar{u}(1 + \nu)$$

$$\Delta P = P_1 - P_2 = \overline{\Delta P}(1 + \varphi)$$

where barred quantities represent steady-state values which are independent of time, and ν and φ are the time-dependent perturbations in velocity and pressure drop, respectively.

Integrating Equation [2] with respect to x

$$\int_1^2 \frac{\partial u}{\partial t}\,dx = -\int_1^2 \frac{\partial}{\partial x}\left(\frac{u^2}{2}\right)dx - \frac{1}{\rho}\int_1^2 \frac{\partial P}{\partial x}\,dx \ldots [3]$$

In performing the integration, we remember that

$$\bar{u} = \bar{u}(x), \qquad \overline{\Delta P} = \overline{\Delta P}(x)$$
$$\nu = \nu(t), \qquad \varphi = \varphi(t)$$

Thus Equation [3] becomes

$$-\frac{d\nu}{dt}\int_1^2 \bar{u}\,dx = \frac{\bar{u}_2^2 - \bar{u}_1^2}{2}(1 + 2\nu + \nu^2) + \frac{\overline{\Delta P}}{\rho}(1 + \varphi) \ldots\ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots [4]$$

But the steady-state velocity $\bar{u}$ at any point in the flow passage may be obtained from the continuity equation

$$\bar{u} = \frac{\bar{u}_2 A_2}{A}$$

and hence the integral on the left-hand side of Equation [4] may be written

$$\int_1^2 \bar{u}\,dx = \bar{u}_2\int_1^2 \frac{A_2}{A}\,dx$$

Using the steady-state Bernoulli equation

$$\frac{\overline{\Delta P}}{\rho} = -\frac{(\bar{u}_2^2 - \bar{u}_1^2)}{2}$$

Equation [4] becomes

$$\varphi = 2\nu + \nu^2 + C\frac{d\nu}{dt}$$

but for small perturbations in the velocity, ν^2 will be negligible and may be dropped. Thus

$$\varphi = 2\nu + C\frac{d\nu}{dt}$$

where

$$C = \frac{2\bar{u}_2\int_1^2 \frac{A_2}{A}\,dx}{\bar{u}_2^2 - \bar{u}_1^2} \quad \ldots\ldots\ldots\ldots\ldots [5]$$

and depends only on steady-state values and geometry of the flow passage.

If now we consider the case of sinusoidal variations in velocity, i.e.,

$$\nu = ae^{i\omega t}$$

$$\varphi = (2 + iC\omega)\nu$$

Expressing this in another form,

$$\varphi = \frac{2}{\cos\alpha}\,\nu e^{i\alpha} \quad \ldots\ldots\ldots\ldots\ldots [6]$$

where

$$\alpha = \tan^{-1} C\omega/2$$

This relationship between flow and pressure perturbations immediately suggests a method for measuring instantaneous flows. Pressure transducers are available (9) with frequency responses in the hundreds of thousands of cycles per second, and thus, if a determination of the value of C in Equation [6] can be made for a given orifice system, it should be possible to obtain instantaneous flow rates directly from the instantaneous pressure drop. The value of C as given by Equation [5] is rather difficult to obtain directly, but an indirect method can be used which depends on the probability that C is independent of frequency. The method consists simply of making actual flow and pressure-drop measurements at low frequencies (e.g., up to 200 cps), using one of the flowmeters to be discussed later in conjunction with two pressure transducers, and fitting the experimental data to Equation [6]. If the value of C determined in this manner does not change over the low frequency range, it is reasonable to assume that it will remain fixed at higher frequencies.

This method is now being investigated at Princeton by D. T. Harrje and F. F. Liu, and the experiments are expected to be completed in the near future. Harrje and Liu are using both the Li mass flowmeter and the hot wire (see later) in conjunction with differential catenary diaphragm strain-gage pressure transducers (9) to determine the instantaneous pressure drop-flow relationship across a particular orifice. Pulsations in the flow rate at frequencies up to 200 cps will be created by sinusoidal variations in the feed-line volume, and measurements of instantaneous flow rate, instantaneous pressure drop, and the phase difference between them will be made.

The method described above clearly illustrates the major difficulty encountered in measuring instantaneous flow rates, namely, the lack of an absolute datum for reference calibration such as is afforded in the case of steady flows by the weighing tank and stopwatch. Even at low frequencies, it is necessary to depend on a mechanism such as the Li mass flowmeter which, although it appears to be an instrument of inherently high frequency response, may certainly introduce the possibility of error.

It is this problem of the lack of a calibration datum which must be overcome before a truly reliable instantaneous flow measurement can be made. At the present time, the only criteria available for determination of reliability in this type of measurement are the validity of the average flow reading and the natural frequency of the instrument in response to a square-pulse input in the flow (such as would be created, for example, by dropping a weight on a piston in the feed line).

If the average flow reading is correct and the natural frequency of the flowmeter is at least twice the required frequency response, it is reasonable to expect a valid reading from the instrument. However, it must be remembered that it is not possible to guarantee any accuracy figure on an instantaneous flow measurement, since there is no standard reference datum with which it can be compared.

Of all the means for measuring instantaneous flow, the most direct is the tank-weighing method. If the feed tank (which must, of course, be isolated from effects of all connecting piping) is mounted or hung on a support or beam of proper cross section to which a strain gage is bonded, the strain gage output can be made directly proportional to the weight of the tank. If the tank weight is then plotted against time, the slope at any point is the instantaneous flow rate at that point. This "flowmeter" has the advantage of simplicity and economy of construction and ease of calibration. However, if the tare weight of the tank is much greater than the liquid capacity (as is usually the case for high-pressure vessels), the sensitivity and frequency response of the measurement are severely impaired. Furthermore, and herein lies the main disadvantage, the strain gages record the flow rate leaving the tank, which may be quite different from, say, the flow rate through the fuel pump or injector nozzle in a jet engine, due to the wave travel time and attenuation introduced by piping, bends, and restrictions in the feed line. Since it is rarely the flow at the tank exit which is desired, but rather the instantaneous rate at some critical point in the feed system, the tank weighing method is not generally applicable to the instantaneous flow-measurement problem. However, if some procedure can be evolved for increasing sensitivity and frequency response, the tank weighing method shows promise as a calibration reference for other flowmeters. For example, M. J. Zucrow of Purdue University has devised an apparatus which measures the change in buoyancy of a long cylindrical body suspended in the tank, reducing the inertia of the sensing element from that of a heavy tank full of liquid to that of a comparatively tiny mass.

Another instrument which has been used for some time to measure instantaneous gas velocities, the hot-wire anemometer (e.g., 10, 11, 12, 13, 14), has recently come into prominence as a possible meter for liquid flows. The basic principle of this device is the well-known fact that the electrical resistance of most metals varies with temperature. If a heated cylinder is mounted in a stream of fluid, the heat transfer from the cylinder will vary with the velocity of the fluid (15) according to the relation

$$\frac{h}{T - T_a} = D + F\sqrt{u} \qquad [7]$$

where

h = rate of heat loss from the wire
T = average wire temperature
T_a = ambient fluid temperature
u = instantaneous fluid velocity
D, F = functions of thermal conductivity, density, and specific heat of the fluid and the dimensions of the wire

If now the wire is heated by an electric current i, heat will be supplied at the rate i^2R, where R is the wire resistance at temperature T. Since the net heat transfer is zero under equilibrium conditions

$$i^2R = h$$

and we obtain the form of the hot-wire relationship

$$\frac{i^2R(R_0\alpha)}{R - R_a} = D + F\sqrt{u} \qquad [8]$$

where

R_a = wire resistance at temperature T_a
R_0 = wire resistance at some reference temperature
α = temperature coefficient of resistance at the reference temperature

The functions D and F are essentially constant, and hence the only variables are the velocity u, the current i, and the wire resistance R. Thus, if the velocity of the flow varies, the current and the resistance will vary accordingly. Since the signal output of a hot-wire meter is usually observed as a voltage difference across a Wheatstone bridge, the variation of both current and resistance makes an adequate measurement impossible. In order to eliminate one of the variables, an electronic feed-back current was designed such that the current through the wire is maintained constant at all times, and hence the instrument signal depends only on variation in resistance (e.g., 16).

A further refinement has been introduced because of the fact that since the wire is of finite size, the surface temperature and core temperature will be different, and the frequency response of the meter thus depends on the time required for thermal equilibrium to be established in the wire. In order to avoid this problem, another electronic feed-back circuit has been devised which varies the current in such a way that the wire temperature, and hence resistance, are maintained constant at all times, and the output signal of the meter is merely this feed-back current. This scheme not only reduces the thermal lag of the wire, permitting it to be used at very high frequencies, but also provides a signal which is linear in the fourth root of the velocity (see Equation [8]). The theory and an experimental investigation of this constant temperature hot wire as applied to air-flow measurements are described in (17) and (18).

The hot-wire anemometer has been highly successful in the measurement of gas velocities, but many problems are encountered in the application of this instrument to liquid flows. One of the major difficulties is the strength problem, since typical wire diameters which are adequate to withstand gas flow forces (e.g., 0.0002 in.) cannot stand up under even the lowest velocity liquid streams. This means that the electrical resistance (which varies inversely as the square of the wire diameter), and hence the sensitivity, are drastically reduced for a wire of given length. Further, heat transfer from the surface of the wire is so rapid in a liquid stream that it is extremely difficult to maintain the wire at a temperature higher than that of the ambient liquid. The use of very high heating currents (19) has resulted generally in boiling of the liquid at the surface of the wire, which completely invalidates the results.

The problem of application of the hot wire to liquid flows is now being investigated at Princeton, using a constant temperature feed-back amplifier and nickel wire of sufficient diameter to prevent breakage in a high-velocity liquid stream, obtaining the required sensitivity by using a long wire wrapped around insulated supports. Although it is doubtful whether the hot wire used in this way will provide adequate amplitude measurements in a pulsating flow, the high heat-transfer rates which prevail in liquids probably insure a thermal time lag sufficiently short so that accurate readings of flow phase can be taken. It is in this application as a "flow phasemeter" that the hot wire shows most promise when used for the measurement of liquids.

The problem of low sensitivity of the hot wire in liquids has recently been attacked by using thermistors (thermally sensitive resistors) as flow sensing elements, instead of simple wires. Thermistors are semiconducting solids whose resistance varies inversely with temperature at very high rates (about 4 per cent per degree centigrade). A description of thermistor characteristics may be found in (20), along with discussions of general applications.

The high thermal sensitivity of thermistors makes them particularly suitable for liquid flow measurements, although their relatively high mass causes a thermal lag which can severely limit the frequency response. An additional, although not insurmountable difficulty is also introduced by the nonlinear relationship of resistance and temperature. Use of thermistors as liquid flowmeters is discussed in (19).

Another flowmeter which has recently come into prominence for instantaneous measurements is the electromagnetic type. Its basic principle of operation is Faraday's law of electromagnetic induction, which states that an electric potential will be established across a conductor which moves through a magnetic field in such a way as to cut the lines of flux. The Faraday law can be derived (21) directly from the Maxwell equation:

$$\nabla \times \mathbf{E} = -\left[\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{V} \times \mathbf{B})\right] = -\frac{d\mathbf{B}}{dt}$$

where

$\mathbf{E}$ = electric field strength
$\mathbf{V}$ = fluid velocity
$\mathbf{B}$ = magnetic field strength

This can be reduced to the more familiar form

$$e = (BdV) \times 10^{-8} \quad [9]$$

where

e = signal potential (volts)
B = magnetic flux density (gauss)
d = conductor length = inner diameter of flowmeter tube (cm)
V = mean fluid velocity (cm/sec)

In the electromagnetic flowmeter, the moving fluid itself forms the conductor (the signal being tapped from electrodes set into the duct walls), and hence it is necessary to use only those fluids whose conductivity is higher than a certain value. This is one of the major shortcomings of this type of instrument, since many of the typical jet engine and rocket fuels are unsatisfactory from this standpoint. For example, one particular design (22) requires a conductivity of 10^{-8} mho/cm^3, which is well out of range of the typical hydrocarbon fuel value of 10^{-11} or 10^{-12} mho/cm^3. Some research has been done on the possibility of increasing conductivity by addition of small amounts of chemical agents such as aerosols (23), but this imposes a restriction which may be difficult to accommodate to fuel performance requirements.

In order to obtain the highest possible frequency response, a constant magnetic field would be most advantageous; however, this introduces a major problem known as polarization. A conducting liquid will electrolyze when an electric current is passed through it, and if this current is always in the same direction, as would be induced by a constant magnetic field, electroysis of the liquid will cause gas to form on the signal pickup electrodes. The nonconducting gas reduces the effective electrode area, changing the effective impedance of the fluid circuit, and the resulting "drift" invalidates the instrument reading. For this reason, most electromagnetic flowmeter designs use an alternating field, although d-c excitation has been used in special cases such as measurement of blood flow through arteries, where the arterial wall itself is a conductor (24). It should be pointed out, however, that the use of conducting material for the fluid duct severely restricts both accuracy and frequency response due to the difficulty of obtaining a truly representative signal at any given location. Other methods are now being considered at Princeton and by the Mittelmann Electronic Company, Chicago, which may permit the use of d-c excitation (e.g., canceling out the d-c signal component by means of a suitable "bucking current," thus eliminating polarization).

The use of an alternating field eliminates polarization, but introduces several additional difficulties. At low excitation frequencies, the response of the instrument is limited, since instead of measuring the flow continuously (as would be the case for d-c excitation), a number of discrete readings corresponding to the pulses of the magnetic field are obtained. If the excitation frequency is increased, the generation of heat as a result of eddy currents induced in the magnet can become troublesome, and, furthermore, a marked increase in required magnet power must be expected. More important, however, is the rapid increase in noise level with magnet frequency in the induced signal circuit, and this factor is the one which is primarily responsible for limiting the excitation frequency and hence the response of the flowmeter.

In spite of these shortcomings, however, the electromagnetic device has many advantages which unquestionably keep it in the instantaneous measurement field. First, the instrument is unique in that no restriction of any sort is required in the fluid passage. The signal is linear in average velocity, as may be seen from Equation [9], and, further, it has been demonstrated that Equation [9] is valid for axially symmetric flows regardless of the velocity distribution (25). This reference also demonstrates that above the conductivity threshold the signal is essentially independent of fluid conductivity. Thus the electromagnetic meter has the excellent feature of being able to measure average flow velocity without being affected by any physical properties of the fluid medium, provided, of course, that the conductivity requirement is met.

Many variations of the basic elements have been built and tested for many applications (e.g., 22, 24, 25, 26, 27, 28, 29). Two instruments which appear to have particular application to rocket and jet propulsion testing (i.e., high pressures and/or flow rates of fluids with low conductivity) are the Mittelmann meter shown in Fig. 9 [Mittelmann Electronic Company (22)]

FIG. 9 MITTELMANN ELECTROMAGNETIC FLOWMETER AND ASSOCIATED EQUIPMENT

and the Arnold meter [James Arnold, New Mexico College, Las Cruces, N. Mex. (26)]. Both of these meters use a nonconducting fluid duct and an alternating magnetic field: 1500 cps in the Mittelmann meter, and 5000 cps in the Arnold instrument. Although Mittelmann's frequency response is low (about 100 cps as compared to about 500 claimed for the Arnold meter), his stability, signal-to-noise ratio, and reproducibility appear to be superior. Both of these designs are to be evaluated experimentally at Princeton in the near future.

The National Bureau of Standards has only recently developed a velocity-measuring device which consists of a pair of piezoelectric crystals mounted in the fluid duct well, one of which is located some distance downstream of the other. Sound waves are then generated by each crystal in turn, being picked up by the other crystal. The difference between the time necessary for the sound wave to move upstream and downstream between the two crystals is measured, and since the distance between the crystals is known, the fluid velocity may be obtained directly.

This system has the advantage of a very high frequency response, limited only by the time required for a sound wave to cover the distance between the crystals. For example, if the pickups are located 1 ft apart, the response in water would be of the order of a few ten thousandths of a second. Unfortunately, no formal publications concerning this instrument are available at the present writing, but additional information may probably be obtained directly from the Bureau of Standards in the very near future.

The most recent development in the flowmeter field is one which appears to best satisfy the requirements for instantaneous measurements in rocket and jet propulsion testing. This is the "true mass rate flowmeter" designed by Li and Lee of the Massachusetts Institute of Technology (30), one particular model of which is shown in Fig. 10. Its principle of operation is illustrated by the schematic diagram of Fig. 11. The fluid flows through a double U-tube which is rotated at constant speed. As the mass flow varies, the angular momentum of the fluid in the radial sections of the inner T-shaped tube changes, and hence the torque required to maintain rotation at constant speed will change. Since the T-shaped tube transmits torque from the motor to the fluid in its radial sections, its deformation will be proportional to the torque and hence to the angular momentum of the fluid. Thus, the torque tube deflection is directly proportional to the angular momentum, or, since the geometry of the system is fixed, to the mass flow.

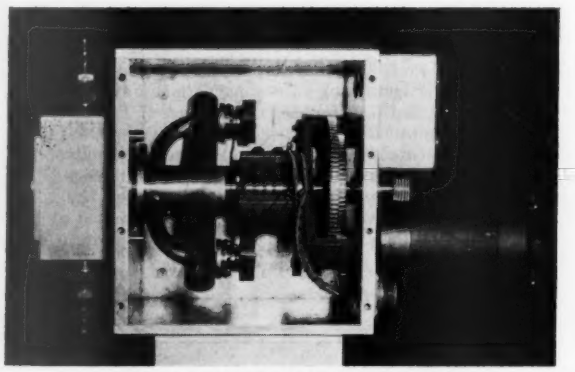

FIG. 10 THE LI MASS RATE FLOWMETER

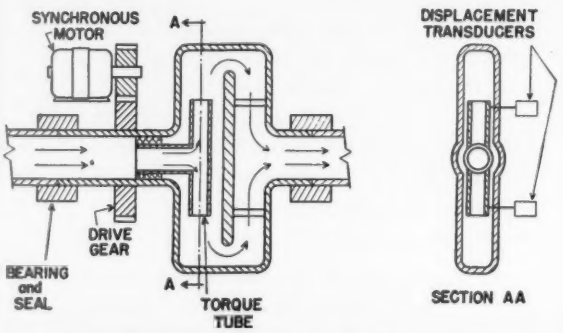

FIG. 11 SCHEMATIC DIAGRAM OF THE LI FLOWMETER

Mathematically, the tangential or "Coriolis force" exerted by the fluid in a radial element of the T-shaped tube of Fig. 11 can be written

$$dF = \rho A a \, dr \quad \ldots\ldots [10]$$

where

ρ = fluid density
A = tube cross-sectional area
a = tangential or Coriolis acceleration
r = radial distance of the element from the axis of rotation

Since the Coriolis acceleration can be written

$$a = 2\omega u$$

where

ω = rotational speed
u = instantaneous flow velocity

and the instantaneous mass rate of flow is given by

$$\frac{dm}{dt} = \rho A u$$

the elemental tangential force becomes

$$dF = 2 \frac{dm}{dt} \omega \, dr$$

or, in terms of elemental torque

$$dT = 2\omega r \frac{dm}{dt} dr$$

The torque on one radial section of the torque tube thus becomes

$$T = \omega l^2 \frac{dm}{dt} \quad \ldots\ldots [11]$$

where

l = length of the radial section
$\frac{dm}{dt}$ = average mass flow rate in the radial section

The hydraulic frequency response is proportional to the mean velocity of flow and inversely proportional to the length of the radial section. For example, if the mean flow velocity is 20 fps and the radial section of the T-tube is 1 in. long, the maximum response obtainable would be 240 cps.

An additional dynamic consideration is that the natural frequency of the elastic system formed by the torque tube must be sufficiently high to assure an elastic system frequency response at least as high as the hydraulic response. The natural frequency of the elastic system is given as (30)

$$f_n = \frac{1}{2\pi} \sqrt{\frac{3}{2} \frac{u\omega r_m}{ld\left(1 + \frac{\rho_t A_t}{\rho A}\right)}} \quad \ldots\ldots [12]$$

where

r_m = radius at which the deflection is measured
d = maximum deflection at measuring point
ρ_t = density of torque tube material
A_t = cross-sectional area of torque tube wall

Equation [12] has been derived for the T-shaped torque tube,

which provides for automatic counterbalancing. The torque tube deflection is measured by a displacement transducer located at a convenient radial distance r_m from the axis of rotation, as shown in Figs. 10 and 11.

The most important feature of the Li mass flowmeter is that it provides direct measurements of true nonsteady mass rates without being affected by pressure, viscosity, density, homogeneity, temperature, or other physical properties of the fluid. Other advantages are its simplicity of installation (Fig. 12), its very low pressure drop (since little restriction is

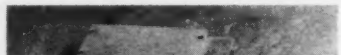

FIG. 12 THE LI MASS FLOWMETER INSTALLATION

offered to the flow), and the fact that its reading is independent of flow direction. Further, the output signal is linear in mass flow rate up to the elastic limit of the torque tube, as indicated by Equation [11], and is entirely unaffected by external accelerations of any sort. The scale of the instrument can be easily shifted by changing the synchronous motor drive gear ratio, although a reduction in speed of rotation decreases the natural frequency as given by Equation [12]. Other construction details may be found in (30).

The only obvious disadvantage is the limitation of frequency response by the necessarily finite length of the torque tube, and until use of this instrument becomes more widespread, no further information is available concerning other possible drawbacks. Evaluation tests made by Li at Massachusetts Institute of Technology are extremely promising, and the results of current studies of special models by Princeton and North American Aviation, Inc., will undoubtedly have an important bearing on the problem of instantaneous flow rate measurements.

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Radio Telemetry[1]

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During the past decade the art of radio telemetry for rockets has grown to become a vital engineering aid in the development of free-flight rockets and guided missiles. This article attempts to familiarize readers of the Journal with significant features of the more generally used telemetry systems, trends which hold possibilities for the future, and an indication of some of the unsolved instrumentation requirements which telemetering will some day be able to answer. A brief reference list, which will lead the reader to a large bibliography of telemetering material, is included.

Introduction

DURING the past 10 years radio telemetry for rockets has been born and reared and has become well developed in conjunction with the missile programs which it has served. No longer does any question exist as to whether or not telemetering methods provide good instrumentation; instead, when a missile program is being initiated, the question is only what system will best provide the data required. Engineering personnel who only a few years ago were loath (or at least hesitant) even to look at telemetered results are now quite willing to accept them as an excellent substitute for the data previously taken in test pits; in many instances, the same engineers have taken telemetering techniques back into the test pit and found them very satisfactory.

Of course the great interest in rockets and guided missiles has stimulated the growth and development of radio telemetering as a replacement for the more common on-board recording techniques commonly used in the development phase of aircraft work. Space, weight, and expendability of rockets have dictated the need for small, light, and highly reliable instrumentation via the radio link.

The large quantity of material on telemetering which has appeared in both the unclassified literature and classified reports gives the newcomer to the field a good foundation on which to work. One of the most thorough reviews of the radio telemetry field is given by Nichols and Rauch (1).[4] Their article was used extensively in the preparation of the following material.

Morphology

The purpose of radio telemetry is to present information available within the test vehicle to the individuals who need such data for the purposes of analysis and evaluation. Within the missile there are generally three important elements: the transducer, the encoding system, and the radio transmission system. A rather elaborate morphological group is made possible by the large quantity of transducers (potentiometers, variable-inductance pickups, strain gages, variable-capacitance pickups, thermocouples, etc.), encoding systems (audiofrequencies with amplitude modulation, AM; audiofrequencies with frequency modulation, FM; pulse-amplitude modulation, PAM; pulse-width modulation, PWM; pulse-time modulation, PTM; etc.), and transmission systems (frequency modulation, FM; phase modulation, PM; amplitude modulation, AM; etc.). In practice it is all too common to consider the transducer apart from the rest of the system and to call the encoding system and radio transmission system the telemeter. Indeed this approach has some merit, for it is not uncommon to find many different types of transducer elements within a single missile; in general, however, they will be gathered for transmission over a single telemeter (e.g., pulse-width modulation—frequency modulation, PWM-FM).

History

When the idea of transmitting data from rockets by radio link was first seriously considered, many organizations began independently to develop telemetering systems (2–7). This uncontrolled interest fostered most of the morphological-system possibilities, each directed at optimum handling of the particular problems of the individual group. Many of these systems were short-lived, and only a few survived to be extensively developed, refined, and eventually available as commercial items. The primary driving force behind the channeling of efforts toward only the most advanced and most promising systems was the Telemetering Working Group of the Panel on Test Range Procedures and Instrumentation of the Research and Development Board. In 1948 one system, FM-FM telemetering, was recognized by this group as the most advanced and was adopted as the RDB standard system. The RDB has since adopted PWM-FM or PWM-PM as a second standard and has encouraged the development of PTM-AM systems. Because of the great influence of this group, which is made up of recognized leaders in the telemetering field, by far the most work has been done, both commercially and by governmental sponsorship, in making the two RDB standard systems available. Most missile test ranges now have complete ground stations capable of receiving and reducing data from these systems (8), whereas for nonstandard systems the individual contractor must supply his own ground station.

General Operation of Systems

Because an FM-FM system is versatile and complex only by multiplicity of circuits, it might be well to describe a system of this type first. This system is one of the earliest to be developed, the original work dating back to 1944. The pioneers in this system were the Jet Propulsion Laboratory (California Institute of Technology), Princeton University, and the Applied Physics Laboratory (Johns Hopkins University). The RDB specifications for an FM-FM system state that the RF carrier shall be within the 215- to 235-mc/sec telemetering band allocated by the Federal Communications Commission; that the deviation of the FM transmitter shall not exceed ±125 kc/sec; and that the modulation will be any desired number of the eighteen standard bands. The bands are specified to include a range of ±7½ per cent around center frequencies in the audio and supersonic frequency spectrum, with a provision for optional

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[2] Guidance Systems Section Chief.

[3] Telemetering Group Leader.

[4] Numbers in parentheses refer to the References on page 145.

wider ranges, ±15 per cent around center frequencies, in the supersonic range. The double FM is formed by letting the parameter to be measured control the frequency of an AF oscillator which operates in one of the bands; the oscillator in turn deviates the RF transmitter center frequency by some fraction of the total deviation by means of a reactance tube or a similar circuit associated with the RF oscillator. More than one measurement requires in general more than one oscillator and an adding circuit to form a complex modulation for the transmitter. This process can continue until difficulties start to arise either from harmonics of one frequency falling in another band or from the subcarrier frequencies becoming too numerous to be conveniently handled on the ground by conventional audio techniques or from other practical limitations. If the data user needs more measurements than can be accommodated on one transmitter as continuous tones, he has two alternatives: the use of a second system complete with airborne transmitter operating at a frequency different from the first, or some method of sharing time in one or more of the bands. The time-sharing method, known as time-division multiplexing, is quite common, both because the two-system operation requires not only two airborne systems but also two ground stations, and because in a great number of cases the data required to specify the variations of a parameter can very satisfactorily be represented as a series of data points. Thus, if one oscillator after another is sampled with a switch of some sort, many measurements can be made in one band. Another technique, depending on the type of measurement being made, includes the successive switching of measurements into the same oscillator. If particular RDB standards for commutation are adhered to, automatic decommutation can be provided by test-range ground equipment (9).

Two basic methods are extensively used to control the subcarrier frequencies; one is to force the parameter being measured to change an air gap in an inductor which is part of an oscillating tuned circuit; the other is to transform the parameter by one of several methods into a voltage which is allowed to vary between the limits of zero and +5 volts with respect to ground. This voltage in turn controls the frequency of a free-running multivibrator, the output of which is passed through a low-pass filter (to eliminate the higher-frequency harmonics) on to the adding circuit. The FM-FM type of system is generally used where provision can be made for considerable weight and space; in general, this type of system includes many vacuum tubes and rather a large primary power source. Fig. 1 shows an FM-FM system developed at the Jet Propulsion Laboratory for research and development work. This system was designed to be easy to modify and service in the field.

Pacific Division of Bendix Aviation Corporation, through its association with the Applied Physics Laboratory, has become a primary supplier of FM-FM equipment, including a rather complete line of variable-inductance gages. Raymond Rosen Engineering Products has specialized in the voltage-controlled FM-FM systems.

To consider the second RDB standard system, PWM-FM, it may be assumed that the transmitter used in the FM-FM system is available; that is, it consists of an oscillator with a reactance tube attached so that a voltage (either a-c or d-c) applied to the input terminals will cause the RF frequency to shift. The transmitter modulation is supplied by a keyer. The purpose of this circuit is to transform a voltage magnitude into a voltage pulse and to maintain a linear relationship between the magnitude of the input and the pulse length in microseconds at the output. For example, the RDB standards state that a 90 ± 30-microsec pulse will correspond to 0 volt, and that a 660 ± 50-microsec pulse will correspond to +5 volts. Operating ahead of the keyer is a commutating switch for sampling more than one measurement voltage. The switch in common use turns at approximately 30 rps and commonly has 30 contacts, two or three of which are used for synchronization of a decommutating device that is a part of the ground station. This system then has a basic capacity of measuring thirty voltages thirty times each second. It can be built to be very compact and is very reliable because of its relative simplicity in number of components required. Even more compact systems have been packaged utilizing this principle but having fewer measurements at a lower sampling rate.

In test vehicles in which the bulk of the required information is already available as voltages or is easily transformed to voltage through a potentiometer transducer, this system has a distinct advantage. Otherwise it suffers from the same difficulty as voltage-controlled FM-FM in which the quantity of electronic circuitry required to transfer the desired measurement into a 0- to 5-volt form may be excessive.

The PWM-FM data take the form of an accurately measurable time interval (pulse width in microseconds) which can be stored on film by photographing each sweep length (equal to the pulse width) as it appears on an oscilloscope-tube face, or which can be manipulated slightly and stored on magnetic tape. A limitation which should be faced is the low-frequency response restriction. Commutating the signals at the rate of thirty samples per second places a maximum theoretical upper limit to the frequency response of 15 cps, or two samples per cycle of a sine wave. In practice, approximately three samples per cycle are required for sine-wave data and more for evaluating complex waves; however, for essentially steady-state data, the system is excellent. This system was pioneered by the General Electric Company and is commonly

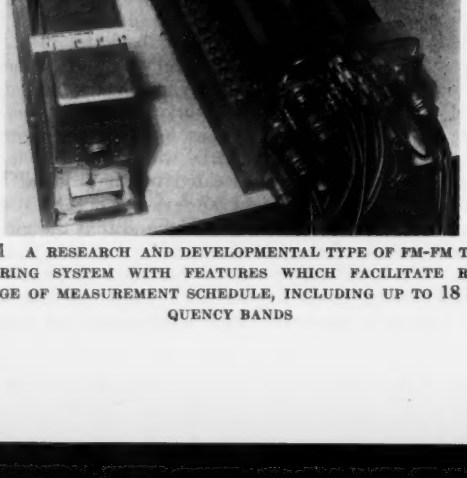

FIG. 1 A RESEARCH AND DEVELOPMENTAL TYPE OF FM-FM TELEMETERING SYSTEM WITH FEATURES WHICH FACILITATE RAPID CHANGE OF MEASUREMENT SCHEDULE, INCLUDING UP TO 18 FREQUENCY BANDS

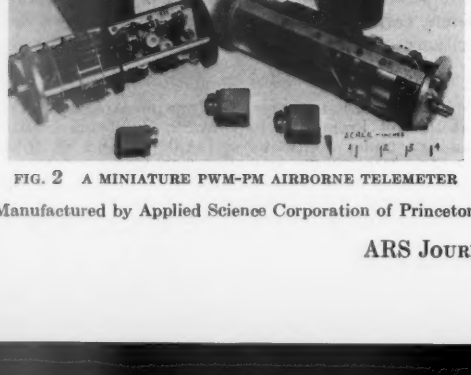

FIG. 2 A MINIATURE PWM-PM AIRBORNE TELEMETER

(Manufactured by Applied Science Corporation of Princeton)

referred to as the Hermes telemetry. At present, it is a commercially available system from the Applied Science Corporation of Princeton (10), in the form shown in Fig. 2.

Over the years of telemetry development there has always been interest in obtaining a telemetering system having a high channel capacity and high-frequency response to handle the data problems of large missiles. It is generally conceded that this system should sample each channel by high-speed electronic switching and, during each sample period, send two pulses wherein the time interval between the pulses represents the desired measurement (PPM-AM). This system should be designed to handle 0- to 5-volt data and bridged-strain-gage data. The Naval Research Laboratory was a pioneer in this field, flying some of its systems in V-2 tests (4) at the White Sands Proving Ground in 1946. The Navy and Air Force have continued to sponsor development of systems to fill this need, but the state of their achievements has not yet brought about acceptance by the RDB of final standards for such a system. The need for such a system continues to exist; when good engineering solutions are found, the RDB will establish the necessary standards, and the test ranges will obtain the required ground equipment. The expansion in recent years of the FM-FM systems from five- and six-channel to fifteen- and eighteen-channel systems can, in some measure, be attributed to the disappointing progress of PPM-AM.

Table I gives an interesting comparison of some of the characteristics of a few operational telemetering systems. This table is patterned after one in the article by Nichols and Rauch (1), but is supplemented by some recent information.

Measurement Techniques

The great percentage of effort involved in making use of any telemeter system is spent in transforming the parameter to be measured into the form required by the system. The simplest method in many cases is to transform the signal into one which is a voltage with limits of 0 and +5 volts for measurement extremes. In the telemetering of data from electronic equipment for guidance or control of a rocket, this approach is excellent because the data generally are in voltage form to begin with, and only the addition of simple divider networks is required. However, when the measurements concern operating pressures, accelerations, relative displacements, and the like, the conversion is somewhat more difficult and involves a transducer or pickup of some kind. In general, the development of transducers for radio telemetry has been carried out by the electronic engineers who have created the telemeter systems. In most cases the transducers have reflected the need of better physical and mechanical background on the part of the instrument designer.

Many kinds of transducers have been successfully used, ranging in complexity from a simple carbon or wire-wound radio potentiometer to the unit shown in Fig. 3, which is a delicate, dual, angular-position indicator costing approximately $800. The first type of transducer is generally used with the simple connection of a voltage source across the end terminals, and the data taken are in terms of the position of the movable arm referred to a fixed voltage point, often one end of the potentiometer.

A second class of transducers can be roughly grouped and called the strain-gage type. These transducers are characterized by a small change in resistance of a resistance wire, usually wound in the form of a grid; this change is derived from the parameter to be measured. For example, a typical bonded-strain-gage installation consists of a wire grid securely fastened to a member which is deformed during test. A calibration is made in terms of the deformation (or the force causing the deformation) and the output from the system. The output may be an a-c or d-c voltage supplied to a secondary circuit, or may be directly a change of frequency of a subcarrier oscillator. The latter is more generally the case in FM-FM systems, and several commercial sources of this type of circuitry exist. Unbonded strain gages have been used quite conveniently to measure pressures and accelerations by winding a grid which has a firm anchor at one end and a movable anchor at the other; for example, the movable anchor may be a diaphragm which is displaced by pressure.

A third class of transducers is characterized by an inductance change caused by a change in the spacing of a movable section of magnetic path in a coil and lamination assembly. Commonly transducers of this type take the form of an E and I assembly with the I attached (*a*) to a diaphragm for pressure measurements; or (*b*) to a spring and mass assembly for acceleration measurements; or (*c*) to a threaded stud, which changes the spacing as the stud is rotated, for measurements of mechanical motion. The advantages of a variable-inductance transducer lie in the ease with which physical parameters such as pressures and accelerations can be transformed to frequency change (particularly in FM-FM systems), and in the avoidance of friction such as is introduced by a potentiometer wiper arm. A disadvantage of variable-inductance transducers is the nonlinear relation which exists between stimulus and frequency in the calibration of such a measurement; however, this effect is often used to advantage by arranging that the region of most interest in the measurement be expanded by letting this region occur when the E and I spacing is smallest.

FIG. 3 AN ANGLE-OF-ATTACK INDICATOR

(Manufactured by G. M. Giannini Company)

TABLE 1 CHARACTERISTICS OF COMMON TELEMETERING SYSTEMS

Type	Number of channels	Number of samples per sec	Frequency response per channel	Tubes per channel	Acceptable signal form	Reference
AM-FM	14	....	200	3	Strain	(11)
FM-FM	16	....	6–2100[a]	1–4	Voltage, variable inductance, variable resistance	(12)
PAM-FM	16	6400	2240	1.7	Voltage only	(2)
PWM-PM	30	30	11	0.2	Voltage only	(10)
PPM-AM	30	312	~100	2+	Voltage only	(5)

[a] Dependent on band width of individual channel.

Miscellaneous other types of transducers have also been extensively used, such as thermocouples and resistance thermometers for temperature measurements, voltage-generating magnet and coil units, piezoelectric crystals for vibration measurements, and variable-capacity microphones for sound and pressure measurements.

Ground Station

The prime function of the ground link of a telemetering system is to record the data transmitted by the airborne equipment. Moreover, the philosophy of the ground station must be that of being able to save the data even when receiving conditions are not favorable, such as exist when the

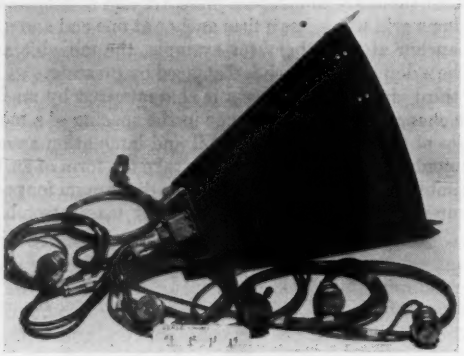

FIG. 4 A PACKAGED 6-CHANNEL FM-FM TELEMETERING SYSTEM

rocket attitude puts the receiving station into a null of the radiation pattern, or when a partial failure occurs in the airborne transmitter. These requirements have led to the development of high-gain antennas, very sensitive low-noise-figure receivers, and even preamplifiers in the RF section of ground stations.

The development of very good magnetic tape recorders (13) as secondary recording measures has covered the possibilities of failure in the primary recorders such as oscilloscope-camera combinations and galvanometer paper-record oscillographs. Tape-recording techniques are now well enough advanced so that it has become quite common to provide secondary coverage even at remote locations (e.g., near impact) by the use of only a receiver and a tape recorder. The tape recording also preserves the maximum of the total received information in that no frequency-response limitations are imposed during the real-time operation, as are found with the use of a recording oscillograph. The tape may be played back innumerable times to optimize the information sought in terms of frequency response, accuracy, etc. Tape recording has also facilitated considerable semiautomatic data reduction of very high accuracy. Telemetry-reduction techniques range all the way from hand replotting of every point of interest to fully automatic systems.

Accuracy

Whereas telemetry is capable of providing the rocket-development engineer with all the frequency response which he will probably ever need, it does not provide all the accuracy desired. Accuracy which equals or betters that obtained in the test pit is attainable but not easy to accomplish in free-flight vehicles in which space and weight are extremely valuable and thee nvironment sometimes is very severe. Telemetry systems (from the transducers through the final graphical data) can be depended upon to yield accuracies of less than 5 per cent of full-scale data, and in general most of the systems are yielding 1 to 2 per cent data consistently. Data of $^1/_2$ per cent and less have been obtained in special instances, but the extreme care required is justified only if the particular item to be measured really warrants such attention.

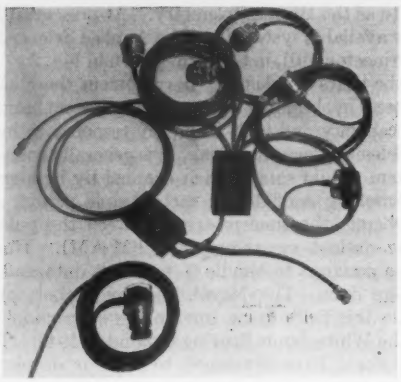

FIG. 5 AN INDICATION OF THE SIZE REDUCTION POSSIBLE BY TRANSISTORIZING THE 6-CHANNEL PACKAGE OF FIG. 4

It is interesting to note that the effective accuracy of data not known to be less than 2 per cent, when cross-checked (made possible by deliberately taking redundant data) in the calculation of the characteristic velocity of a rocket motor, has frequently proved to be less than $^1/_2$ per cent.

Future Developments

One of the greatest factors which will influence telemetering developments during the next few years will be the application of new circuit elements such as the transistor (14). The advantages of decreased volume, weight, and power requirements are of too great importance not to be exploited greatly for airborne equipments. Fig. 4 shows the size and form of a typically packaged FM-FM system now in use, whereas Fig. 5 shows the decrease in size possible when the same measurements are transistorized. In the lower left-hand corner of Fig. 5 may be seen an experimental packaging of the transistor oscillator on the transducer, a design concept which may become quite practical. Work in this direction points an accusing finger at the size of the transducer, which now becomes much larger than the auxiliary circuitry. In a number of organizations people are working continuously on transistor-circuit development directly applicable to telemetering, and it is expected that a few transistorized systems will be flown within this year.

A second trend will be toward more conservative use of the RF spectrum. The large test ranges are even now finding interferences due to multiple telemetry operation and transmitter-frequency instability. Developments will probably take the form of crystal controlled—phase modulated and crystal referenced—frequency modulated transmitters. In addition, specific frequency allocations to major users of telemetering systems may be made.

Another, and perhaps the most important facet of the telemetering field, that of transducers, must certainly be advanced. The units available now are far from optimum in versatility, size, weight, construction, and cost. Manufacturers and users alike will recognize that the usefulness and reliability of a transducer need not be proportionate to its cost, and that fancy machined surfaces and multiple adjustments are not necessarily of great advantage. Improved systems will result as the transducer designs are made more and more a part of the integrated telemetering-system design.

Future work will also be aimed at techniques for solving a few of the thorny problems which have arisen during the past few years: (*a*) What is the mass of the missile at any given time in flight? (*b*) What is the drag acceleration of the missile to the nearest 0.1 ft/sec^2? (*c*) How can continuous measurement of the air density be made? Considerable work has been done in the past few years in gathering upper air data, and a period of analysis of those data has now been reached (15). The results of this analysis will doubtless suggest many new and interesting experiments.

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Recording Instruments in Rocket and Jet Engine Testing

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The available recording instruments used to receive the output of the standard transducers normally associated with rocket and jet engine testing are reviewed here. Mechanical recorders, self-balancing potentiometers, magnetic oscillographs, cathode-ray oscillographs, and magnetic tape recorders are discussed and compared with respect to response time, accuracy, flexibility, ease of maintenance, cost, etc. Emphasis is placed on tape recording as the newest tool for high-response recording and analysis.

IN THE instrumentation system, regardless of which quantity is to be measured or which transducing device is to be used, a method of recording or indication is desirable that will be practical to install and maintain and the most useful for the expenditure involved. Above all, the method should present the data in their most significant form. It is the intent of this article to survey available recording instruments to aid the engineer in his choice of an instrument for a particular job. As it is assumed that most test engineers will be familiar with conventional instruments, emphasis is placed on newer developments.

General

Recording of rocket chamber test data normally requires the use of slow, medium, and fast-response equipment, the rate depending upon the test program. In lieu of more complete response information and of the lack of standardization in referring to response, it is assumed the following definitions are applicable to rocket testing operations: (*a*) Slow response—average reading instruments, heavily damped, slower than 0.5 second. (*b*) Medium response—average reading follows and indicates slow variations, response from 0.5 to 0.001 second. (*c*) Fast response—for transient work; will not reproduce records of some detonations or other extremely fast phenomena, but will reproduce most mechanically excited variations; response is faster than 0.001 second, usually at least 0.0001 second.

Although a controversial point, the response time of an instrument is defined as the time required for the instrument to come to rest at the correct value after a step function has been applied to the sensing device.

The ability of an instrument to record a fluctuating input either as a true average value or as a faithful reproduction of the input wave form is essential. Dependence upon average value for general performance evaluation is customary, whereas high-speed instruments are generally used either for troubleshooting in a rocket system or for basic investigations in burning or instability phenomena.

Mechanical Recorders-Pressure Gages

In the field of recording instruments, probably the most simple and basic unit is the recording pressure gage. This device was formerly the standard in the combustion field. Various combinations of auxiliary equipment permit the recording gage to read not only pressure, but also flow, thrust, temperature, and other quantities. The sizable internal volume in either Bourdon tube or bellows type instrument results in a response that is slow, uncertain, and subject to wide variations dependent on whether the instrument lines are air-filled or bled down. Many are still in use in the jet propulsion field, but they are being replaced wherever possible by improved methods. The advantages of simplicity, ease of maintenance, and small original investment are outweighed by the poor or variable response characteristics, difficulties in telemetering or distant reading, corrosion problems in the instrument and associated lines, and safety considerations.

Self-Balancing Potentiometer Recorders

In the field of recorders used to measure average quantities, the self-balancing potentiometer recorder has a place of preeminence. These instruments operate on the electrical output of any of several transducers or sensing elements discussed elsewhere in this issue. Most such recorders are null balance devices operating on a Wheatstone bridge principle. A motor-operated movable contact on the "slide wire" is used as the measuring device. Some recorders, for which dependability is claimed to be superior, are operated on an inductive bridge principle. Here a-c is applied to the balancing circuit and reactive elements are used to balance the circuit. Either circular chart or strip chart instruments are available from most manufacturers.

The precision of the potentiometer recorder is ±0.25 per cent in most cases, but, of course, the accuracy of the final system must be determined in each case independently. Most instruments suitable for use in the rocket testing field should have a full-scale travel in two seconds or less to be really usable. Brown Instrument Division, Minneapolis-Honeywell Corporation,[1] has announced a half-second recorder. Naturally, some allowance must be made in a fast pen speed instrument for a wider dead zone, or point of indeterminate balance, and consequently accuracies of ±0.25 per cent should not be expected of this particular unit. Also the minimum span available is 10 millivolt, which may be too insensitive in a few applications using strain gages. All recorders of 1-second full scale or slower can be obtained with a 1-millivolt span, and in special applications, 100-microvolt instruments are available, although a much slower pen travel is to be expected.

The potentiometer recorder can be adapted easily for remote indication, controlling, high or low cutoffs using limit switches, and numerous other uses. Their cost ranges $600 up, depending upon the specialty required in the individual instrument.

Many useful variations of the instrument are available, some of which can be most useful in data analysis and readout of final data direct from rocket tests. A dual channel instrument recording 2 channels on a single chart is available which might be arranged to display fuel and oxidizer flow. An "X-Y" recorder which could be used to display any two variables, one plotted against the other, is available from both Leeds and Northrup Company, and Brown Instrument. Thrust vs. chamber pressure, or even, by a very simple arrangement, thrust vs. mixture ratio, can be set up and displayed directly from test data.

A variable range instrument is available for use in flexible installations, such as the multichannel setup for the recording

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[1] For further details about any instrument mentioned in this manuscript, reference should be made to the literature supplied by the manufacturers listed in the References on page 149.

of a large number of strain-gage channels. One instrument is available which has variable ranges from 1 to 50 millivolt full-scale and zero suppression equivalent to full scale on all ranges.

Of all the instruments available to the test engineer, the potentiometer recorder probably is the most flexible in its applicability to special tasks. It is, furthermore, reasonably dependable and, if skilled personnel are available, easy to maintain. Manufacturers are Brown Instrument, Leeds and Northrup Company, Bristol Company, Weston Electrical Instrument Corporation, Foxboro Corporation, and others.

Direct Writing Oscillographs

For faster responses than are available with the recording potentiometer, it is necessary to go to the magnetic, direct writing oscillograph. A D'Arsonval movement to which a pen is attached and which is operated from a power amplifier permits a maximum response of 0.01 second. This is about as fast as it is possible to go in a direct writing instrument.

A chart width of from $1^5/_8$ to 2 in. is provided in the equipment by the Brush Development Company, and about the same in that by the Sanborn Company, and Edin Electronics Company. As a result of this limited readability and unstable nature of associated electronic components, these instruments are primarily for use in valve timing and other special installations, rather than for use as a tool for performance evaluation. A precision figure of ± 10 per cent over-all is about the limit that can be obtained without special steps such as some method of continuous calibration. Recorders are available in various combinations of input types. A common type of amplifier input made by all manufacturers operates from strain gages. D-c amplifiers are available, which when used with preamplifiers, make possible direct recording from thermocouples. Recorders are manufactured in 1-, 2-, 4-, and 6-channel instruments. Not all combinations are obtainable from any one manufacturer. Most are available now in either rack mounting or portable type units. Strain-gage and d-c inputs are usually interchangeable in multichannel systems.

Magnetic Oscillographs

In order to achieve higher speed records, early attempts were made to so reduce the mass of an indicating device as to permit the direct recording in a graphic presentation of audio or sound frequencies. The present magnetic oscillographs are a direct outgrowth of these attempts.

Many concerns now make very acceptable instruments, all competitive, with very convenient and flexible control arrangements and a wide selection of replaceable galvonometers. As limits of response are increased, sensitivity is reduced and it is thus not possible to assign exact limits of either. As an example, however, it is possible to record without amplification the output of strain-gage type sensing devices and obtain deflections of 3 in. at about 100 cps.

For multichannel installations, oscillographs are made with 48 channels operating independently on 12-in. paper.

Operating conveniences are: Quick change gears for 4 to 6 speeds, automatic exposure control upon speed change, automatic record numbering, malfunction indicator lamps, trace interruptor which interrupts each trace successively so that positive trace identification is always possible even though traces cross, and other features.

Excellent amplifiers are available from the manufacturer of the units so that higher responses as well as sensitivity can be achieved.

As this type of recorder depends upon photographic techniques, provisions must be made for the handling of long lengths of whatever width paper is required. A continuous developer costing $1875 is available to accomplish this end, but a serviceable device can be provided which costs considerably less. Care must always be taken that oscillographic records are not submitted to undue stress while wet, since measurements of trace deflection would be thereby distorted and rendered inaccurate.

Manufacturers of magnetic oscillographs are Consolidated Engineering Corporation, Miller, Midwestern Geophysical Laboratory, Heiland Research Corporation, etc.

Cathode-Ray Oscillographs

The fastest response obtainable optically is through the use of cathode-ray recording. As electron beams have essentially no inertia, the limitation of mechanical movement is now removed, and the limits of response are defined by readability, the time required to expose a photographic emulsion. A secondary limit is placed upon response by the frequency response of the electrical circuitry, but this is usually very much higher than the highest frequency that is to be recorded in rocket test data.

The problem of extending response limits becomes one of devising faster-moving film traverses, faster lenses and emulsions, and brighter traces on the cathode-ray tube screens. In general, most records are limited in response primarily by the lack of definition presently available in the commercial types of oscillographs. These limitations are caused by the interference of adjacent cycles in recording any oscillatory phenomena. In the case of recording a single transient, much advanced work has been done by Allen B. Du Mont Laboratories, Inc. Traces now have been very clearly recorded with electrical pulses as short as 0.1 microsecond. Any mechanical or thermodynamic process will produce effects very much slower than this, and so it can be readily seen that the electronic and photographic processes are sufficiently fast to record most phenomena encountered in the rocket field.

Any modern oscillograph with a reasonably high accelerating potential and a good focus is satisfactory for most work. Extreme brilliance and definition are essential for the faster recording.

In rocket testing, the most common moving-film camera is the Fairchild Oscillo-Record Camera. It comes with an $f1.9$ lens and a film speed adjustable from 10 in. per min to 60 in. per sec. With a modern oscilloscope from which to record, a sine wave frequency of about 5000 to 7000 cycles per sec can be obtained on 35-mm film. If individual transients are recorded, higher writing speeds are possible; but in recording the type of data obtained in rocket testing it is probable that, due to interference and lack of definition in the recorded line, the above limits are not far out of line.

Multichannel recording is also possible by several methods. One method is through the use of a high-frequency electronic switch so arranged as to display successively each channel for a discreet time. This method is fairly satisfactory where reasonably slow phenomena are taking place. It falls down due to periodic interruption of each channel when really fast response is called for. In the search for a method where continuous presentation from each channel is possible, arrangements of a number of separate cathode-ray tubes with lenses and prisms to record on one film were tried. The Heiland Research Corporation manufactured such an instrument, and satisfactory records were made with this instrument.

At present, a very satisfactory recorder in two- and four-channel types is made by the Electronic Tube Corporation. The heart of this instrument is the four- (or two-) gun cathode-ray tube, where each of the separate electron guns is focused on the same screen. Each gun is equipped with its own electronic circuitry, and thus independent records can be made for each of the channels. Since time reference is maintained exactly, the advantage of such a unit is obvious.

To provide positive trace identification, an electronic trace interrupter can be incorporated in the device without much expense or difficulty and similar in effect to the interrupter in the magnetic oscillograph.

Magnetic Tape Recording

Although to date it has found somewhat limited acceptance in the field, magnetic recording has many features which recommend its use in the recording of data from rocket tests. To really understand these features of the newest type of

recording, it is necessary to pursue this subject somewhat more thoroughly than has been done with the more conventional instruments.

Although early efforts in the magnetic recording field in Germany culminated in 1937 with the design of very acceptable magnetic recorders, little resemblance to modern recorders is seen in these early instruments. It was not until the war effort demonstrated the need for a cheap and convenient method of recording sound that the perfection of any recording devices of this nature took place commercially. This was in the form of the familiar "wire recorder" using 420 stainless wire, 1 mil in diameter. The Armour Research Foundation and the Brush Development Company took the lead in the development and promotion of this medium.

The search for an improved method of recording was not dropped here, however. Wire recording had a number of faults, among them the inconsistency caused by rotation of the wire between recording and playback, resulting in uncertain reproduction of the high frequencies and the speed variation caused by uneven stacking of the wire on the takeup reel.

The search led to steel tape and finally to the present form of coated plastic tape. The state of the art has permitted refinements in both backing and coating so that today's tape with very finely divided and evenly deposited iron oxide has been developed to give repeatable and predictable performance.

Any transducer or sensing element which provides an electrical output may be recorded on magnetic tape. Auxiliary equipment is often necessary, primarily for purposes of calibration or retention of accuracy in amplitude.

Of primary interest in the rocket propulsion field is the application of magnetic recording to test data. This includes pressures, temperatures, thrusts, etc. When this type of data is recorded it must be noted that certain limitations are inherent in magnetic recording.

Let us first consider the frequency response of the recorder. Intelligence is recorded on the medium by the impressing of alternate poles, north and south, upon the tape by means of the recording head. This process is somewhat complicated by the addition to the desired signal of a supersonic a-c bias. This process is a pure addition, not a modulation. The purpose of the bias is to permit a linear relationship to exist between the amplitude of playback output and the applied flux. Since the transfer characteristic of any magnetic material is nonlinear, the remanent magnetism or flux formed in the recording process is nonlinear with respect to the recording current. The effect of the bias is to cause the poles formed in the recording process to approximate, providing that the value of bias is large in amplitude with respect to the recorded data and high in frequency, a point of remanent flux linearly related to the recording current.

The highest frequency which can be recorded is then primarily a function of bias frequency, recording head gap width, and tape speed. The latter two items are related to the highest recordable frequency because the shortest wave length which can be recorded is limited by the smallest distance which can be maintained between discrete poles on the tape. The bias is usually about 4 to 5 times the highest frequency to be recorded to prevent the formation of beat notes and does not itself record on the tape. The modern tape recorder can deliver about 1 kc per inch of tape speed per second.

The low frequencies present a different sort of problem. As wave lengths to be recorded approach the actual dimensions of the recording head pole pieces, instability in amplitude takes place due to interferences across the gap and pole pieces. Also, since output from tape is proportional to rate of change of flux, output drops lower and lower, reaching zero at d-c.

Two types of recording are used for data storage: direct amplitude recording in the range of 100 to 60,000 cycles per second; and FM recording in which a carrier is used permitting recording down to d-c and in which 0 to 5000 cycles per second is a common range, and in 0 to 12,000 cycles per second an approximate upper limit.

For later observation and analysis, direct amplitude recording is ideal for recording of transients, periodic functions, and digital information of certain types. Pressure fluctuations in rocket systems are often recorded in this manner. The two disadvantages of direct recording are its inability to record static levels of input data, and the relatively high uncertainty in amplitude caused by tape characteristics. These include thickness variation, magnetic condition of the tape before recording, and nodules in the tape which are condensations of magnetic material which cause minor fluctuations in recorded output amplitude. Approximately 10 per cent variation in amplitude on the average can be expected from these causes. Some improvement can be expected through the use of preselected tape, which is tape that has been chosen for its high degree of uniformity and lack of nodules.

Calibration must be done at a frequency in the range of the recorder. For calibrating a pressure recording channel, for example, it is first necessary to arrive at a d-c sensitivity figure of voltage output for the pressure, and convert this to a-c sensitivity at a suitable frequency. The sensing element is then operated from a d-c energizing source, and output fluctuations are recorded proportionally to pressure fluctuation. No static level of pressure is recorded since in this type of system only an a-c voltage having an average value of zero can be recorded. As a result, if the pressure being recorded is stable, a very low level recording will be made, regardless of the static pressure existing in the system. However, when oscillatory combustion or other instability occurs in some process, fluctuations in the transmission range of the recorder are recorded and their amplitude can be determined from the magnitude of the voltage played back, as read, on a voltmeter or oscillograph. Other methods of data analysis will be discussed later.

Data recording soon showed the need for a d-c response tape recorder that is particularly useful for data telemetered from missiles. A recorder of this type can maintain a zero reference other than true zero. Calibration and data analysis thus becomes easier. A direct calibration by either known d-c inputs or by direct application of the quantity to be measured in known levels is now possible. In analysis of data, very easy correlation between instability and level of operation or between different quantities is feasible.

To achieve d-c response by the FM method, an oscillator generating a frequency near the upper limit of the recorder is frequency modulated by the data from a sensing element, and the output of the oscillator is recorded on the tape. A typical carrier frequency for a tape speed of 60 in. per second is 45 kc, and the frequency response of this recorder would then be 0 to 10,000 cycles. If the tape speed is reduced, the upper recordable limit is reduced proportionally. When recording in the FM system, no bias is required since the carrier itself does not have to be recorded linearly.

The performance of the system as developed by the Ampex Electric Company, Inc., is very satisfactory for recording the data from rocket tests. The signal-to-noise ratio is 40 db below full recording level, response is ± 2 db from 0 to 10,000 cycles per second at 60 ips, and, if line voltage is regulated, the drift from all causes is less than $1/2$ per cent.

Mention must be made of speed control since it is intimately associated with the faithful recording and reproduction of data. Data recording places a much tighter restriction on the control of the tape speed than does the recording of speech or music. In nearly all tape instruments, tape speed is controlled by a capstan drive. This drive consists of a constant speed capstan driven by a synchronous motor, and a rubber idler which presses the tape against the capstan to minimize slippage. Motor speed is definitely dependent upon line frequency, which is normally well controlled. If a field power supply is used, however, as might be the case with a portable installation, it is possible to procure a constant frequency generator, a source of accurately controlled 60-cycle current to operate the drive motor.

To compensate for changes in frequency at the time of recording the original record, or for changes in tape length due to stretch or shrinkage of the tape, a power drive for the capstan motor is available which operates from a control track recorded at the time the original record was made. A correction signal is derived also to increase or decrease the speed of the capstan motor as required to exactly match the speed of the original recording.

In FM systems, variations in speed introduce spurious modulations of the recorded carrier. These show up as noise, either random or periodic, depending upon the cause of the speed variation or flutter, as it is called. The limiting factor upon improved signal-to-noise ratio is the inability to provide absolutely smooth traverse of the tape. Therefore, the utmost in careful design and precision manufacture is necessary to insure minimum flutter. In one instrument made by Ampex, a large perforated capstan is used with a series of peripheral holes to be attached to a vacuum pump to minimize slippage. To avoid any possibility of localized tape stretching between heads and capstan, the heads are mounted so as to bear directly upon the tape as it is passing around the capstan. An electronic method of removing the effect of the residual flutter has been devised for use in an FM system. Here the output from a control channel is used in conjunction with each of the data channels to subtract any FM caused by flutter that appears upon the control channel from the data channels.

These and other facets of tape recording should be treated more thoroughly. The potentialities are great in this field, and, although much is left to be done to make the instruments better and more economical, they are now a very attractive medium for data recording in the rocket field. The original relatively high cost can very frequently be justified by the saving in man hours in analysis, in having one instrument that can be called upon to do the work of several conventional type recorders, and the large saving in the total amount of chart paper and photographic film and paper that must be expended, of which fully 50 per cent to 90 per cent is useless. Magnetic tape can be reproduced apparently indefinitely with little or no loss in fidelity of reproduction, and can be erased and re-used repeatedly.

Multichannel recording is always of great interest in rocket work or aeronautical data recording of any type. Tape recorders are available with up to 14 channels of data recorded simultaneously on 1-in. wide tape. Either direct recording in amplitude, FM, or a mixture of both can be used.

Occasionally, d-c response combined with response higher than 10,000 cycles per second is required for a given measurement. At the present state of the art, this is not possible in one channel, but, since extended responses as high as 100,000 cycles can be recorded if d-c response is not required, use of a channel set up for each method of recording is feasible and useful.

Separate instruments for recording and playback can be obtained if it is desired to analyze data in a location removed from the testing site. The cost of separate instruments is naturally more because the mechanical details of both instruments are similar, and both must have equally good speed control if the full capabilities are to be realized.

If data have been recorded on tape only, it is necessary first to obtain the average or static information through the use of an average reading voltmeter or recording potentiometer. Note that all channels can be played back through a single instrument, and, if a strip chart recorder is used and proper timing indications are placed upon the record from the strip chart instrument, time reference as good as if the data were taken originally on the strip chart recorder will be obtained.

The next step will be to examine those portions of any test results where interest lies; e.g., a short screaming period or other malfunctioning of a rocket during a firing. Photographing portions of the test results on film where required is often helpful in an understanding of what took place. Here the tape recorder, although primarily only a method of data storage, can be used to assist in analysis. It is possible, by recording at a high speed and playing back at a lower speed, to reduce the frequency noted, or to slow down transients, still preserving the wave shape and the phase relationship between channels. An extension of the range of usability of the moving film camera by this method of as much as 30 to 1 can be accomplished, if necessary. Also, the tape can be edited by cutting and splicing before the data are recorded on the film, thereby cutting to a minimum the wastage of film in the process.

The procedure in data analysis from here on is dependent upon a variety of factors, such as the type of data recorded, the ultimate purpose of the test, etc. Instruments are available for the measurement of frequency, amplitude, phase difference, pulse count, etc. A very useful device for this work is the sound spectrum analyzer. Normally used to plot the amplitude vs. frequency content of a complex audio wave form, it is a useful device in the analysis of data where either incipient or high intensity screaming occurs. The sonic analyzer completes a sweep from 20 to 20,000 cycles once each second, displaying upon a cathode-ray tube a plot of the relative amplitude of each frequency component. Instruments to accomplish this end have been made by Kaye Electric Company and Panoramic Radio Company.

When exacting requirements make it necessary to accurately determine power at a given frequency or band of frequencies, an electrical filter can be used. Several manufacturers at present make adjustable filters of sufficiently wide range to perform any sort of analysis of this type.

To facilitate analysis of this type, using tape-recorded data, sections of the tape can be cut out, spliced end to end, and played back as a continuous loop. This permits more detailed analysis and allows time for a detailed examination which would not have been possible during the actual test run.

Many details concerning recorders have been necessarily left out and other phases curtailed due to space limitations. Advances are being made continually in accuracy, flexibility and dependability, not to mention, in the case of tape recording, a reduction in the price of most models. It is hoped that the subjects mentioned here and compared in Table 1 will suggest instruments and applications of use to the reader.

TABLE 1 COMPARISON OF RECORDING INSTRUMENTS

Type	Response	Accuracy, %	Maintenance	Safety	Stability	Dependability	Flexibility	Dollar cost (per channel)
Pneumatic or direct reading	2–5 sec	±2	Excellent	Poor	Good	Good	Fair	60–250
Self-balancing potentiometer	0.5–4 sec	±1/2	Good	Good	Good	Good	Excellent	550–750
Magnetic, direct-inking oscillograph	0.01 sec	±10	Fair	Good	Poor	Fair	Fair	700–1000
Magnetic, photographic oscillograph	0.02 sec–0.0005 sec	±2	Fair	Good	Fair	Fair	Good	250–500
Cathode ray	0.00005 sec	±5	Poor	Good	Fair	Fair	Good	1000–1200
Magnetic tape FM	0–15 kc	±2	Poor	Good	Good	Fair	Good	2000
Magnetic tape AM	100 cps, 60 kc	±10	Poor	Good	Fair	Fair	Good	1200

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Reduction of Rocket Motor Performance Data by Means of IBM Computing Machines[1]

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A method for calculating experimental rocket motor performance and heat transfer data on IBM machines is described. The instrumentation calibration procedure and methods for transferring calibration and run data from the recording instruments to IBM cards are outlined. The procedure followed for calculating these data on IBM machines is described and a brief description of the machines employed is included. An approximate time study and cost analysis for the IBM method of reducing rocket motor performance and heat transfer data is included.

1 Introduction

THE Rocket Laboratory of Purdue University is conducting fundamental studies of rocket motor performance and heat transfer at increased combustion pressures. A large quantity of data reduction is involved that normally requires plotting calibration curves, selecting the run points and time-consuming calculations with either a hand or electrically operated calculating machine. Frequently, the reduction of the data obtained from a test delayed the experimental program because the results were unavailable early enough for planning the next test. In December of 1951 it was decided, at the suggestion of Dr. M. J. Zucrow, Professor of Gas Turbines and Jet Propulsion, to investigate the possibility of applying IBM computing machines to the reduction of the data obtained.

The Computation Laboratory of Purdue University was organized a few years ago to aid those departments and experimental groups at the University needing statistical and computation assistance. The Computation Laboratory is staffed with trained personnel who can recommend and develop the most suitable procedure for employing the computing machines available at the Laboratory. It was decided after consultations between the Rocket and Computation Laboratory staffs, that the IBM punch-card machines were most suited to the reduction of rocket motor performance data, and would give the desired information faster and cheaper than the normal procedures that were being employed. Many other sciences had successfully employed punched cards in the reduction of data (1).[4] To apply the IBM machines would involve merely transferring the test data from the records of the rocket motor test to the IBM punch cards.

[1] This research program was conducted under the auspices of Project SQUID sponsored jointly by the Office of Naval Research and the Office of Air Research under Contract N6ori-104, and is presently to be continued by the sponsorship of the Office of Naval Research under Contract N7onr-39418.

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[3] Graduate Student, Purdue University Computational Laboratory.

[4] Numbers in parentheses refer to the References on page 154.

FIG. 1 CENTRAL RECORDING PANEL AT PURDUE UNIVERSITY ROCKET LABORATORY

2 Description of Instrumentation at the Rocket Laboratory

All of the variables measured during a rocket motor test, except the coolant water flow rate, are recorded by electrical recording instruments operated by reluctance transducer elements. The latter translate such variables as force (thrust), pressure, and differential pressure into electrical signals. The force transducer signal originates in the deflection of a ring, while the pressure and differential pressure signals are derived from the deflections of twisted tubes. The electrical signals from the transducers are linear functions of the measured variable as long as the stress on the transducer element is below the elastic limit of the materials employed for constructing either the ring or twisted tube. The above stress-strain relationship for the transducer elements makes it a relatively simple matter to fit an equation (straight line) to the calibration data for each transducer element.

The pertinent temperatures for calculating the heat transfer for the rocket motor walls are measured by iron-constantan thermocouples connected directly to automatic-balancing recording potentiometers. The output from the transducers, discussed above, are also recorded on automatic-balancing recording potentiometers. The later instruments are mounted on the Central Recording Panel illustrated in Fig. 1. Each electrical transducer channel connected to one of the recording potentiometers is equipped with a range adjustment and a zero adjustment. The range for each variable is adjusted to give nearly full scale deflection of the potentiometer pen at normal operating conditions, thus giving the maximum reading accuracy in reading the record. The zero adjustment makes it possible to set the same zero on the recorders during a calibration test and an actual rocket test, thereby eliminating an addition or subtraction process in reducing the test data.

The force, pressure, and differential pressure pickups are calibrated immediately before and immediately after each rocket firing test. A typical thrust chart from the recording potentiometer is illustrated in Fig. 2; a calibration test is recorded on the same chart on each side (before and after) of the firing test record. Force transducers are employed for measuring thrust, and propellant tank weights. They are calibrated by loading the thrust parallelogram and the tanks with calibrated weights. All of the pressure transducers incorporated in the measuring system are arranged so that they can be connected to a common chamber, which is pressurized with nitrogen gas through a pressure regulator, and are calibrated simultaneously. Readings of the calibrating pressure are indicated on a 12-in. Heise pressure gage; the Heise pressure gage, together with the pressure regulator are shown at the lower right-hand side of the Central Recording Panel in Fig. 1. The differential pressure transducers are calibrated in a similar manner. One side is loaded with a regulated air pressure which is read on a Heise pressure gage, and the other side is open to the atmosphere. The inherent zero shift in the differential pressure transducers under high static pressure is compensated for by means of the afore-mentioned zero adjustment incorporated in the pertinent channel.

Cooling water flow rates are measured by flowrators and the readings are recorded on a pressure recorder, the lower instrument at the extreme right of the Central Recording Panel (Fig. 1).

3 Transfer of the Recorded Data to the IBM Cards

The measured variables are divided into two groups; Group A, those varying with time, and Group B, those invariant with time (see Table 1). The readings for the variables in Group A are recorded on the strip charts of the potentiometers that are graduated in deg F. These recorded data are transferred to the IBM cards at specified intervals of running time, selected by the test engineer. Each set of IBM cards is prepunched and stamped with the name of the variable to which the set applies and the code numbers and symbols employed by the Computation Laboratory. Each time interval requires a separate card for a given variable. This information was punched into the cards employing the 517 Gang Punch. The punched information was then printed on the top of the card by the Type 552 Interpreter. Readings at 5-sec intervals are normally transferred to the cards for tests of 30- to 50-sec durations. For example, eight cards in the same set are marked for the thrust data obtained from a 40-sec run; no card is required for zero time. A sample thrust card marked for a running point at 25 sec, for which the potentiometer chart reading was 363 F, is shown in Fig. 3. The time, 25 seconds, is marked on the left-hand side of the card and the chart reading of 363 is marked on the right-hand side. The decimal point is located between the X's marked at the top of the card.

The variables in Group B, Table 1, those invariant with

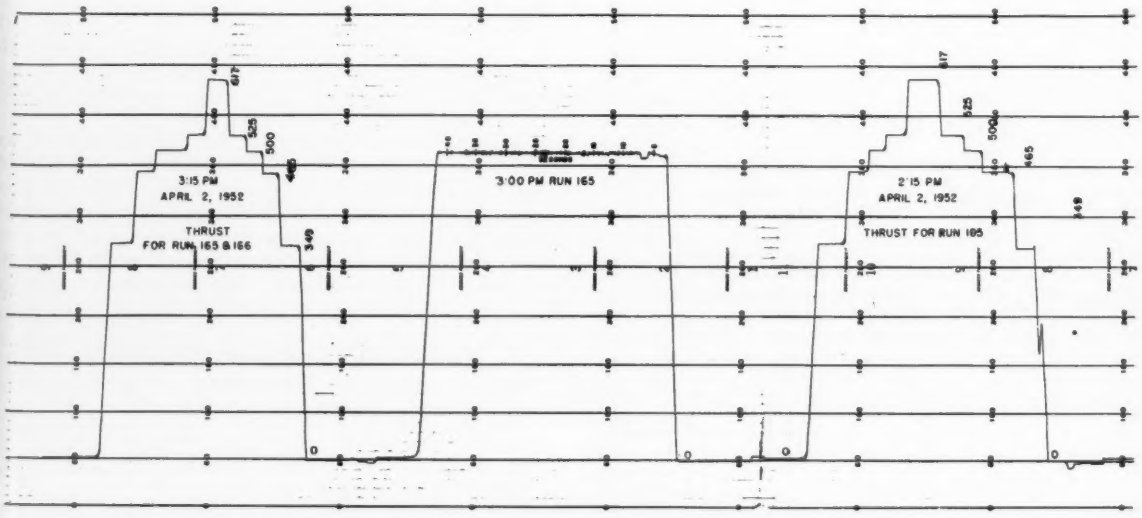

FIG. 2 BROWN CHART FOR THRUST SHOWING CALIBRATION AND TEST RUN

time, are measured before and after a run. In the case of a variable which tends to change its value slightly during the run, its average value is employed in the calculations. Variables which may have the foregoing characteristics are: (1) Nozzle throat area. (2) Fuel specific gravity. (3) Oxidizer

TABLE 1 VARIABLES MEASURED

Group A (variable with time)

1 Thrust, deg F
2 Combustion chamber pressure, deg F
3 Fuel injection pressure, deg F
4 Oxidizer injection pressure, deg F
5 Fuel tank pressure, deg F
6 Oxidizer tank pressure, deg F
7 Fuel flowmeter differential pressure, deg F
8 Oxidizer flowmeter differential pressure, deg F
9 Nozzle coolant flow rate, lb/sec
10 Chamber coolant flow rate, lb/sec
11 Coolant inlet temperature, deg F
12 Nozzle coolant outlet temperature, deg F
13 Chamber coolant outlet temperature, deg F

Group B (invariant with time)

1 Nozzle throat area, in.^{2}
2 Chamber heat-transfer surface area, in.^{2}
3 Oxidizer specific gravity
4 Barometric pressure, inches of Hg
5 Nozzle heat-transfer surface area, in.^{2}
6 Fuel flowmeter orifice area, in.^{2}
7 Oxidizer flowmeter orifice area, in.^{2}
8 Fuel flowmeter orifice coefficient
9 Oxidizer flowmeter orifice coefficient
10 Fuel specific gravity

specific gravity. (4) Barometric pressure. The remaining variables in Group B are assumed to be constants. One card is required for each of these variables. A sample card for nozzle throat area is presented in Fig. 4, and is marked for a nozzle throat area of 1.173 sq in.

The running-point cards (applies to variables in Group A) and the single-point cards (applies to variables in Group B) are marked by one person. All of the cards for a run of 40-sec duration can be marked in 20 to 30 min. A complete run of 40 sec requires marking a total of 114 running-point and single-point cards.

The parameters which are calibrated before and after each run in terms of deg F on the recording potentiometer charts, are: (1) Thrust, F vs. lb. (2) Combustion chamber pressure, F vs. psig. (3) Fuel injector pressure, F vs. psig. (4) Oxidizer injector pressure, F vs. psig. (5) Fuel tank pressure, F vs. psig. (6) Oxidizer tank pressure, F vs. psig. (7) Fuel flowmeter differential pressure, F vs. psi. (8) Oxidizer flowmeter differential pressure, F vs. psi.

Each calibration point is transferred to a single IBM card. Fig. 5 is a sample calibration card for thrust, and indicates that a thrust of 465 lb is equivalent to 342 deg F on the potentiometer strip chart. The calibration points are normally

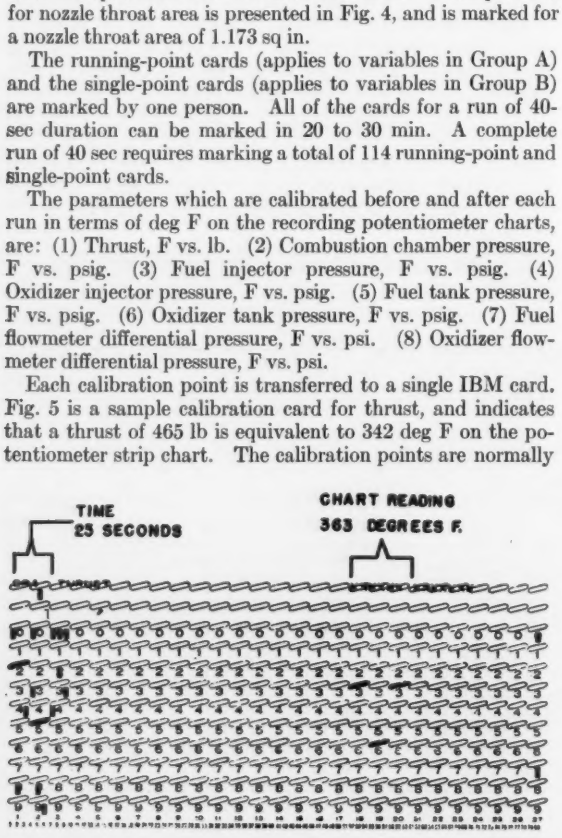

FIG. 3 THRUST RUNNING-POINT CARD. THE RECORD READS 363 F AT 25 SEC

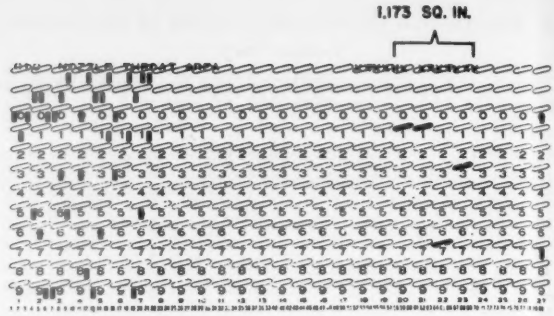

FIG. 4 NOZZLE-THROAT AREA CARD INDICATING AN AREA OF 1.173 SQ IN.

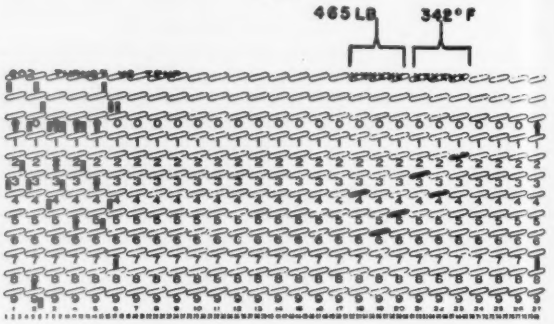

FIG. 5 THRUST CALIBRATION CARD. A THRUST OF 465 LB IS EQUIVALENT TO A READING OF 342 F ON THE CHART

transferred from the strip charts to the IBM cards by two persons: one reading the values from the chart, and the other marking the cards. It is possible to mark the IBM cards with the calibration information while the calibration is taking place; the instrumentation engineer records the measured values on the strip chart and reads them to the card marker. It was found, however, that such a procedure increased the length of time required to perform the calibration, and was abandoned. The foregoing procedure might be improved by employing a third person to read the measured values to the card marker after the instrumentation engineer has recorded them on the strip chart. The marking of the calibration cards consumes the largest portion of time required to mark a complete set of cards for a single rocket test. If a calibration precedes and follows each rocket run, which is the procedure at the Purdue Rocket Laboratory, approximately 40 to 50 minutes are consumed in marking the calibration cards. If two or more runs are made with a calibration between each run, then one set of calibration cards can be used for two runs, thereby reducing the portion of the time required for marking calibration cards.

Table 2 presents the parameters and calculations which are computed by the Computation Laboratory. The marked cards are turned over to technicians at the Computation Laboratory. Spot checks are made, by the test engineer, of the differential pressures for measuring flow rates, chamber pressure, and thrust, and his results serve as a check on the results obtained with IBM machines.

4 Method of Calculating the Data on IBM Machines

The following IBM machines are utilized in reducing the data:[5] Type 602 Multiplying Punch; Type 080 Sorter; Type 513 Reproducer; Type 405 Tabulator; Type 517 Gang Punch; Type 552 Interpreter.

The 602 Multiplying Punch is capable of both multiplication and division, taking the factors from a card and punching

the result on the same card. To obtain either operation a control panel must be wired and inserted into the machine. For the reduction of rocket motor performance data, a special, card-controlled, sequence control panel was designed which permits either multiplication or division and also internal storage of the intermediate results. The cards which contain the factors also contain control punching which instructs the machine as to which operation to perform and, also, whether to punch the result or store it for use in a later calculation.

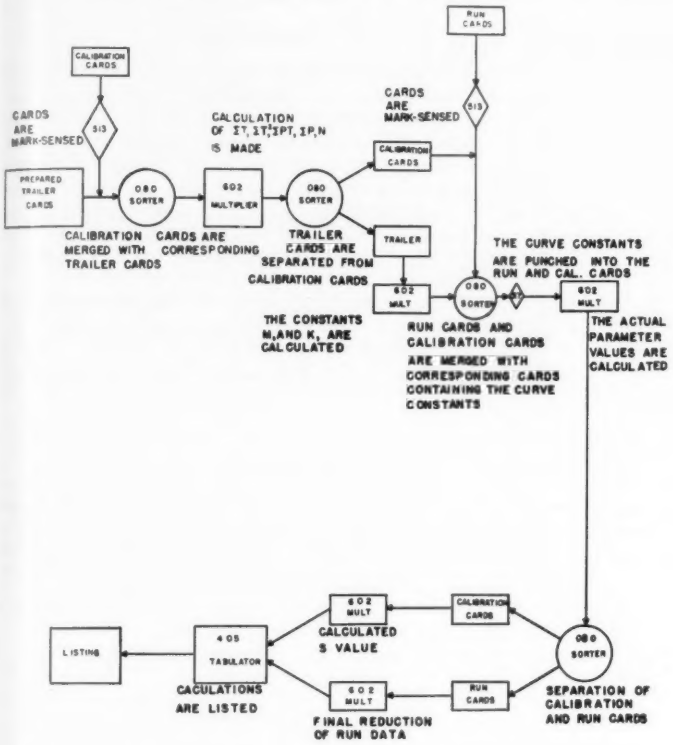

FIG. 6 FLOW DIAGRAM FOR CALCULATING ROCKET MOTOR DATA BY MEANS OF IBM MACHINES

TABLE 2 PARAMETERS AND CALCULATIONS REQUIRED FOR EACH RUN

A One value for each time unit
1 Thrust, lb
2 Combustion chamber pressure, psig
3 Fuel injection pressure, psig
4 Oxidizer injection pressure, psig
5 Fuel tank pressure, psig
6 Oxidizer tank pressure, psig
7 Fuel injector pressure drop, psi
8 Oxidizer injector pressure drop, psi
9 Fuel line pressure drop, psi
10 Oxidizer line pressure drop, psi
11 Fuel flow rate, lb/sec
12 Oxidizer flow rate, lb/sec
13 Total propellant flow rate, lb/sec
14 Propellant mixture ratio, oxidizer/fuel by weight
15 Specific inpulse, sec
16 Characteristic velocity, ft/sec
17 Thrust coefficient
18 Nozzle heat-transfer rate per unit area, Btu/in.^{2}-sec
19 Chamber heat-transfer rate per unit area, Btu/in.^{2}-sec
20 Total heat-transferred rate to coolant, Btu/sec

B Run calibrations
1 Equation for thrust calibration and S value
2 Equation for chamber pressure calibration and S value
3 Equation for fuel injector pressure calibration and S value
4 Equation for oxidizer injector pressure calibration and S value
5 Equation for fuel tank pressure calibration and S value
6 Equation for oxidizer tank pressure calibration and S value
7 Equation for fuel flow differential pressure calibration and S value
8 Equation for oxidizer flow differential pressure calibration and S value

When the cards arrive from the Rocket Laboratory, the first operation is to "mark sense" the cards, which is a procedure for converting the marking corresponding to the value of the observed data and time interval into punches in the same card. A run number is also punched into each card for identification. The flow diagram for calculating the rocket motor data is illustrated in Fig. 6.

The next step is to calculate the constants m and k for each calibration curve. Due to the linearity of the electrical transducer signals, the calibration curve for any variable, such as p, is given by

$$p_c = mT + k \quad \ldots\ldots\ldots\ldots [1]$$

where T is the observed chart reading, and p_c is the calculated value of the variable p in question, corresponding to the recorded value of T. The constants m and k are obtained by solving the following simultaneous equations which are determined by the method of least squares

$$kN + m \sum T = \sum p_0$$

$$k \sum T + m \sum T^2 = \sum p_0 T \quad \ldots\ldots [2]$$

Here, N is the total number of observations, $\sum T$ is the sum of the observed chart readings, and $\sum p_0$ is the sum of the observed values for the variable p, etc. The solution to Equation [2] can be written in the form

$$m = \frac{N(\sum p_0 T) - (\sum p_0)(\sum T)}{N \sum T^2 - (\sum T)^2}$$

and

$$k = \frac{\sum p_0 - m \sum T}{N} \quad \ldots\ldots\ldots\ldots [3]$$

The values of N, $\sum T$, $\sum T^2$, $\sum p_0$, and $\sum p_0 T$ are obtained by running the calibration cards through the 602 Multiplying Punch. As each card passes through the machine, the values of p_0 and T are read in, and T^2 and $p_0 T$ are calculated. The numbers are then accumulated until all the cards for a particular calibration have passed through, at which time the sums are punched into "trailer" cards. This operation requires a specially wired control panel.

The next step is to calculate the curve constants m and k from Equations [3]. This operation is also performed on the 602 Multiplying Punch, utilizing the special card-controlled sequence control panel mentioned earlier. The trailer cards from the previous run are used as "factor input cards."

The curve constants are then gang-punched into the calibration cards and the running-point cards containing the rocket test data. The Type 517 Gang Punch essentially punches identical information into a given set of cards. The values of the variables (1 through 8 in Group A, Table 1), which are recorded in deg F on the charts, are then calculated on the 602 Multiplying Punch from the equation $p_c = mT +$

[5] Information concerning the principles of operation and use of these machines may be obtained from the International Business Machine Corporation (2).

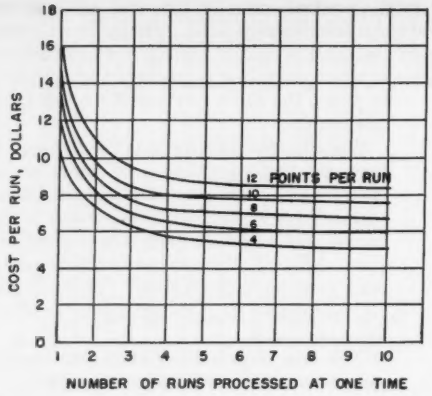

FIG. 7 VARIATION OF COST PER RUN, FOR CALCULATING ROCKET MOTOR DATA ON IBM MACHINES, WITH NUMBER OF RUNS PROCESSED AT ONE TIME AND NUMBER OF OPERATING POINTS AT WHICH DATA ARE CALCULATED FOR EACH RUN

k. The running-point cards now bear the data necessary for calculating the performance parameters listed in Table 2A, and the calibration cards are punched with both the observed values and the calculated values from the calibration equation.

The "goodness of fit" of the calibration curve to the calibration points is determined, so that the accuracy of the calculated parameter can be estimated. The most commonly used measure is the S values or "standard error of the estimated parameter", which is defined as the root-mean-square average of the difference between the observed and the calculated values of the parameter (3).

$$S = \sqrt{\frac{1}{N} \sum (p_0 - p_c)^2}$$

The terms p_0 and p_c are the observed and calculated values, respectively, of the parameter p. It is shown in the theory of probability that approximately 68 per cent of the observed values of the parameter can be expected to fall within $p_c \pm S$, 95.5 per cent within $p_c \pm 2S$, and 99.7 per cent within $p_c \pm 3S$. The S values are calculated directly by first computing $p_0 - p_c$, then squaring, summing, and performing the division by N. A specially wired control panel is then used to complete the calculation by extracting the square root.

The last calculation is the final reduction of the data, performed by the 602 Multiplying Punch using the card-controlled sequence control panel. The results of the reduction, the original input data, the curve constants, and the S values are then listed by running the cards through the 405 Tabulator which is equipped with an appropriately wired control panel.

The total cost of the calculations is dependent on the number of time intervals calculated, and the number of runs processed at one time. The cost per run decreases with the number of runs processed at one time and increases with the number of points calculated for each run as shown in Fig. 7. Fig. 7 was based on the experience gained to date in performing the calculations listed in Table 2 at 5-sec intervals for each rocket motor run.

The Purdue Computational Laboratory has just received an IBM card-programmed electronic calculator. This machine is a combination tabulator, electronic multiplier, and summary punch augmented by auxiliary storage units for internal memory of constants and intermediate results. As implied in the name, the arithmetic unit operates at electronic speed. With such a machine, the complete calculations will be performed in one process, using the marked cards supplied by the Rocket Laboratory augmented by "program" or instruction cards all sorted together in proper sequence. With this equipment the cost may be substantially reduced and the time of processing will be reduced to a fraction of that required at present.

5 Conclusions

Many improvements can be made to the method of data reduction described above. The method employed will generally be dictated by the initial cost of the IBM installation and the speed and accuracy desired for the calculations. One improvement would be the utilization of automatic transcription devices which operate directly from the recording instruments and punch the data into cards automatically. Such an installation would be economical only if there were enough volume of data to keep the machine operating practically full time.

In conclusion, our experience with the described method of reducing rocket motor test data has proved it to be an improvement over the conventional method. It is faster, more accurate, cheaper, and more economical in the use of technical manpower.

References

1 "Proceedings of the Computation Seminar," International Business Machines Corporation, New York, August 1951.

2 "IBM Electric Punched Card Accounting Machines—Principles of Operation" (Calculating Punch Type 602), International Business Machines Corporation, New York, 1947.

3 "Elements of Statistics," by E. B. Mode, Prentice-Hall Publishing Co., New York, 2nd edition, 1951.

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The Measurement of Gas Temperature by Immersion-Type Instruments

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National Bureau of Standards, Washington, D. C.

Available methods and instruments for measuring the temperatures of gases in turbines and jet engines by means of sensing elements immersed in the working medium are reviewed and intercompared. Means for reducing and evaluating the effects of radiation and gas impact upon the performance of the instrument are shown to be of considerable importance in such applications. For purposes of engine control and protection, the rate of response to sudden changes in temperature is also of particular interest. These characteristics, together with ranges of applicability and methods of construction and insulation required to withstand engine-operating conditions, are discussed for bare, sheathed, shielded, and aspirated thermocouples, for resistance-type elements, and for several pneumatic or thermodynamic systems.

THE growing demand for gas turbines and jet engines with increased power output and higher efficiencies has created urgent need for additional research and development of methods and improved instruments for measuring the temperatures of flowing gases. Progress toward more compact and efficient power plants involves the handling and utilization of the working media at ever higher temperatures, pressures, and velocities. The increasing severity of operating conditions, together with demands for higher precision and more rapid response, have made it desirable to re-examine certain characteristics of temperature-sensing devices which were of minor importance in many previous applications.

The present review of methods for measuring the temperatures of gases in turbines and jet engines is limited to instruments whose sensing elements are immersed in the working medium. Since metal and alloy parts are involved, the upper limit of applicability of such instruments is fixed by the melting points of the more refractory metals, which coincide roughly with the peak temperature (ca. 3800° F) attainable in air-breathing engines using hydrocarbon fuels. The higher temperatures experienced in many rockets can be measured only by spectroscopic techniques, which are discussed elsewhere in this issue of the JOURNAL by Dyne and Penner (1).[2]

Although the space available for this paper does not permit presentation of detailed descriptions or inclusion of a complete bibliography, the sources mentioned in (2) list hundreds of reports containing further information in this field.

General Considerations

The basic laws governing the heat transfer between an immersed body and its surroundings are reviewed only briefly here. The steady-state temperature attained by an immersed sensing element is determined by equality of the rates of heat transfer to and from the element. When no chemical reaction is occurring, such a balance exists among processes which include convection, conduction, radiation, friction, and impact, the latter two being considered here as one and called the impact effect. Since it is the temperature of the immersed element that is measured, the major problem in accurate thermometry is to bring the sensing element as nearly as practicable to the gas temperature.

In ordinary engine applications of immersed instruments the surrounding walls are cooler than the working medium and the sensing element. Under these conditions both conduction along solid parts of the instrument and radiation from the element to the walls tend to make the element run cooler than the gas. Radiant heat exchange with the gas itself is relatively unimportant because its emissivity is normally low, and because the temperature difference between the gas and the element is small.

Conduction

Heat loss by conduction along the instrument itself is seldom a serious problem, since its rate can usually be made negligibly small by proper design and by immersion to an adequate depth.

Radiation

When the sensing element and the surrounding walls are at absolute temperatures of T_i and T_w, respectively, the rate of radiant heat loss by the element is proportional to $\sigma\epsilon(T_i^4 - T_w^4)$, in which σ is the Stefan-Boltzmann constant, and ϵ is the surface emissivity of the element. Although the emissivity of the walls is normally high, its actual value is unimportant since the wall area is so many times that of the element. The rate of radiant heat loss can be reduced by radiation shields of various sorts. The actual thermometric error due to radiation depends upon both the rate of heat loss by radiation and the ratio of this rate to the rate of heat gain by convection.

Convection

The primary process by which an object immersed in flowing gas gains heat is direct convection. Based on an empirical formulation of many data, McAdams (3) found that the coefficient of heat transfer by convection from a flowing gas to small wires is approximately proportional to the square root of the mass flow rate. Thus, even though the temperatures of the gas and the walls around an immersed instrument are kept constant, the steady-state temperature which the instrument attains will vary in like manner with the mass flow rate, so long as there is heat loss by conduction and radiation. The resultant thermometric error at the steady state is determined by the relative rates of heat gain and loss.

The practical importance of this fact can be illustrated by considering a bare base metal thermocouple installed in a hypothetical engine in which the gas temperature and velocity and the wall temperature remain constant during a climb, while the static pressure and mass flow rate at the thermocouple decrease to one ninth the original values. The thermometric error at the higher altitude will then be approximately three times as great as it was at the lower altitude. For the same reason, a given sensing element will respond only one third as rapidly at the high as at the low altitude.

[1] Physicist.

[2] Numbers in parentheses refer to the References on page 164.

Thus, convection plays a most important role in the thermometry of flowing gases and, while not generally subject to control in th efree stream, certain immersion-type instruments, to be described later, have been designed to include means for increasing the convective heat transfer to the sensing elements above its value in the free stream.

Impact

In stagnant gases, temperature is a measure of the mean kinetic energy of random motion of the molecules. However, in many gas streams which find current application, the directed velocity is appreciable as compared with the mean velocity of random molecular motion. In such cases the two temperatures of interest are the static temperature (T_s) which would be indicated by an error-free instrument moving with the gas, and the total temperature (T_t), which would be indicated by an error-free instrument immersed in the gas after it had been brought to rest reversibly and adiabatically. These temperatures are related through the familiar equations

$$T_t - T_s = V^2/2gJC_p, \text{ and } T_t/T_s = 1 + M^2(\gamma - 1)/2 \ldots [1]$$

in which V is gas velocity, g is the gravitational constant, J is the mechanical equivalent of heat, C_p is the heat capacity of the gas at constant pressure, M is the Mach number, and γ is the ratio of the specific heat at constant pressure to that at constant volume.

A stationary bare thermocouple, otherwise error-free, will attain neither T_t nor T_s when immersed in flowing gas, but rather some intermediate temperature T_i, whose value depends upon how completely the directed velocity of the gas is converted into random molecular motion upon impact with the sensing element. Obviously such conversion can be promoted by surrounding the thermocouple with a stagnation chamber, thus forming the familiar total temperature probe.

The capacity of an instrument for converting directed kinetic energy into random thermal energy can be specified in terms of the recovery factor r, defined as

$$r = (T_i - T_s)/(T_t - T_s) \ldots [2]$$

which is readily measurable. Experiments have shown that the recovery factor of a given instrument is sensibly independent of the temperature level and of the free stream velocity, throughout that portion of the subsonic range in which no local shock waves are created by virtue of the flow around the unit.

Fig. 1 illustrates the combined effect of radiation and impact on the temperature attained by a typical, bare Chromel-Alumel thermocouple ($r = 0.65$) in flowing gas at $P_s = 1$ atm when the surrounding walls are at a temperature T_w of 1000° F. One curve in each rectangle gives T_t for the gas, one its T_s, and the third shows the temperature T_i attained and indicated by the junction. The upper set of curves applies when T_s is constant at 1500° F and the lower when $T_t = 1500°$ F. In both cases the effect of radiation decreases and that of impact increases with velocity, causing the thermocouple to indicate exactly the static temperature of the gas when the velocity is approximately 800 fps. This figure shows the magnitude of the error that can arise from radiation and impact unless proper corrections are applied.

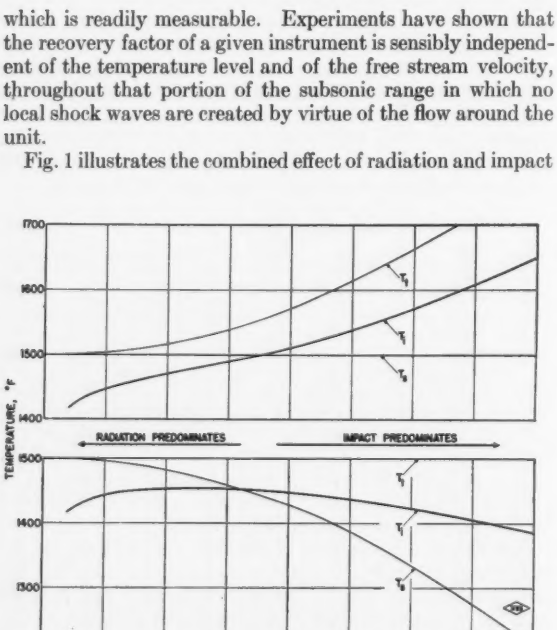

FIG. 1 COMBINED EFFECT OF RADIATION AND IMPACT ON THE PERFORMANCE OF A TYPICAL BARE CHROMEL-ALUMEL THERMOCOUPLE HAVING A RECOVERY FACTOR OF 0.65. ASSUMED CONSTANT: $T_w = 1000°$F; $P_s = 1$ ATM

Rate of Response

In engine-control systems actuated by a device sensitive to gas temperature, the rate of response of the sensing element to sudden changes in the gas temperature is of considerable importance. When the gas temperature is changed instantaneously from T_1 to T_2, the change in temperature ΔT experienced by a thermocouple in any time t thereafter is given by the relation

$$\Delta T = (T_2 - T_1)(1 - e^{-t/\tau}) \ldots [3]$$

in which e is the base of Naperian logarithms and τ is a constant. The constant τ depends primarily upon the mass and heat capacity of the junction and upon the rate of heat transfer by convection from the gas to the junction. The latter, in turn, is a function of the mass flow rate and of the shape of the junction.

From Equation [3] it is apparent that τ has the dimension of time, and that at time $t = \tau$ the junction has experienced $1 - 1/e = 63.2$ per cent of the total change in temperature to which it was subjected instantaneously. The time τ, as just specified, is called the characteristic time of the sensing element. More detailed discussions of the characteristic times of temperature sensing elements are to be found in the literature (4). The τ of an object immersed in gas flowing at velocities attained in jet engines is essentially independent of the temperature level and of the temperature change to which the object is subjected, and the same value of τ applies whether it is being heated or cooled. Since τ varies with flow rate, numerical values are significant only when this rate is specified. The τ of a given sensing element depends primarily upon its mass, heat capacity, and shape, the latter determining the rate at which it receives heat by convection. Typical curves for bare thermocouple junctions are presented in Fig. 2 to show the effects of wire size and mass flow rate on τ. Unfortunately it is not practical to use thermocouples made from fine wire in engines because they lack the necessary resistance to impact and vibration.

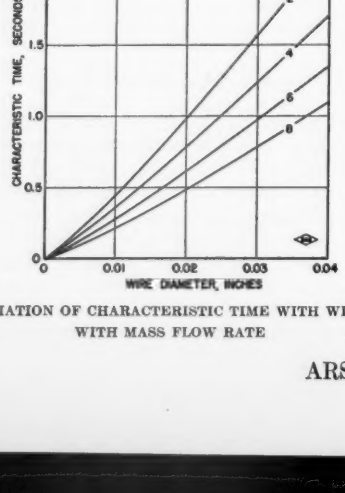

FIG. 2 VARIATION OF CHARACTERISTIC TIME WITH WIRE SIZE AND WITH MASS FLOW RATE

Corrosion

An instrument installed in an engine using pure hydrocarbon fuel and air may be exposed to either oxidizing or reducing atmospheres. The most destructive condition seems to be when these occur alternately. Fuels made from petroleum containing varying small amounts of sulfur burn to corrosive oxides. Aviation gasoline contains small amounts of lead tetraethyl, ethylene dibromide, and ethylene dichloride, and the products of its combustion contain oxides and halides of lead, and possibly other halides. Immersed instruments must withstand attack by these compounds. It is possible that, if heavy residual oils containing vanadium salts are burned, still another corrosion problem may be encountered.

The possibility of oxidation by exhaust gas requires that metals of the tungsten group be protected, and has thus far precluded their use as exposed thermocouples or resistance thermometers. The most widely used base metal thermoelements, Chromel and Alumel, as well as the platinum metals, have adequate resistance to oxidation and reduction. However, Alumel deteriorates by intergranular corrosion, a process which seems to be accelerated in the presence of sulfur. It is believed that lead compounds also affect Alumel, and they would undoubtedly contaminate the platinum metals.

Mechanical Stresses

The mechanical stresses to which an instrument immersed in the working medium of an aviation power plant is subjected are much higher than had been anticipated. It was a major undertaking to develop thermocouples which had adequate mechanical strength in turbojet engines, and particularly in such engines with afterburners. High frequency vibrations, with accelerations in the range up to 1000 g, have been experienced. To withstand such conditions, bare thermocouples must be made of heavier wire than is desirable from the standpoint of response rate, supporting tubes must be strong, and the insulation must be and remain in intimate contact with both the support tube and the thermoelements.

While intergranular corrosion is without sensible effect on the thermoelectric properties of Alumel, it is accompanied by rapid failure from fatigue. The search for another alloy for use with Chromel has yielded a few with suitable mechanical properties and corrosion resistance, but none having more than about half the thermal emf of Chromel-Alumel.

Bare thermocouples must also have adequate mechanical strength under service conditions to withstand the impact of high-velocity gas. In this respect, platinum-platinum rhodium couples are inferior, while Chromel, Alumel, iridium, and alloys of iridium with rhodium are adequate. Metals of the tungsten group also have adequate mechanical strength, which is another reason for seeking coatings which will protect them from oxidation.

The various immersion-type instruments and methods applicable for measuring the temperatures of flowing gases will now be reviewed, with particular attention to the characteristics and possible sources of error mentioned previously.

Immersed Instruments for Measuring Gas Temperatures

Because of the wide range of operating conditions encountered in gas turbines and jet engines, no single temperature-measuring instrument or method is suitable for all applications. The selection of an instrument for a particular application should be made on the basis of the temperature, composition and flow rate of the gas, the space available, the relative severity of radiation and velocity conditions, the accuracy, response rate, and mechanical strength required, and the characteristics of available indicating and recording equipment. Of all the immersion-type instruments available, by far the most common ones utilize thermocouples or resistance thermometers as the sensing elements. Targets for optical and radiation pyrometers are also of this type. Various systems based on the drop in pressure through an orifice or a nozzle in series with a similar constriction have been studied as means for determining gas temperature. Each of these instruments, as well as others less familiar, has advantages and practical limitations which will be discussed in the sections which follow.

Thermocouples

The thermocouple (2c, pp. 4-8) is at present the most widely used instrument for measuring gas temperature in engines, and will be treated in considerable detail. Comparatively few combinations of metals and alloys have been found useful for thermocouples, so that the choice of elements for a particular application is quite limited. Table 1 lists the thermocouples which are useful at elevated temperatures, together with the upper temperature limit and the average dE/dT over specified ranges. The abbreviations used hereafter for the various alloys, and some remarks concerning important characteristics of several of the elements, are also included.

TABLE 1 CHARACTERISTICS OF HIGH-TEMPERATURE THERMOCOUPLES

Thermoelements	Abbreviation	Temp Limit, °F	dE/dT in Range Specified		Remarks
			$\mu v/°F$		
Chromel-Constantan	Ch-Kn	1400	42	(32–1400)	Kn oxidizes rapidly above 1400°F
Iron-Constantan	Fe-Kn	1400	32	(32–1400)	Both oxidize, Fe rusts
Chromel-Alumel	Ch-Alu	2200	23	(32–2200)	Alu shows intergranular corrosion accelerated greatly by sulfur and probably by lead
Platinum vs. 90%-Pt 10% Rhodium	Pt-Pt Rh	2650	6.3	(1200–2650)	Both very soft. Catalytic action, particularly at low temperatures
Iridium vs. 50%-Ir 50% Rh	Ir-Ir Rh	3700	2.9	(2000–3700)	Thermocouple-grade material not yet available. Too brittle for bending. Strength adequate if not bumped. Expensive

Bare and Sheathed Junctions. Where rapid response is desired, the use of bare junctions is generally required. Thermoelements of Fe and Kn are short lived at elevated temperatures in oxidizing atmospheres. Advantage can be taken of the high thermal emf of Ch-Kn in only those applications where short life can be tolerated. Thermocouples of Ch-Alu are widely used in turbojet engines, but a substitute for Alu may be needed for adequate life as the sulfur content of fuels increases.

In engine service, bare junctions of base metals become coated with oxide which may serve as protection unless flaked off by rapid temperature cycling. Such oxides usually have emissivities greater than 0.8, so that losses by radiation may be important. Unless coated by deposits from the gas, thermoelements of the platinum group have emissivities of about 0.2, so that their loss by radiation is about one fourth that of base metals under the same temperature conditions.

From the standpoint of ability to withstand impact and vibration, there are several problems in the use of bare junctions. First, the projecting junction must be self-supporting

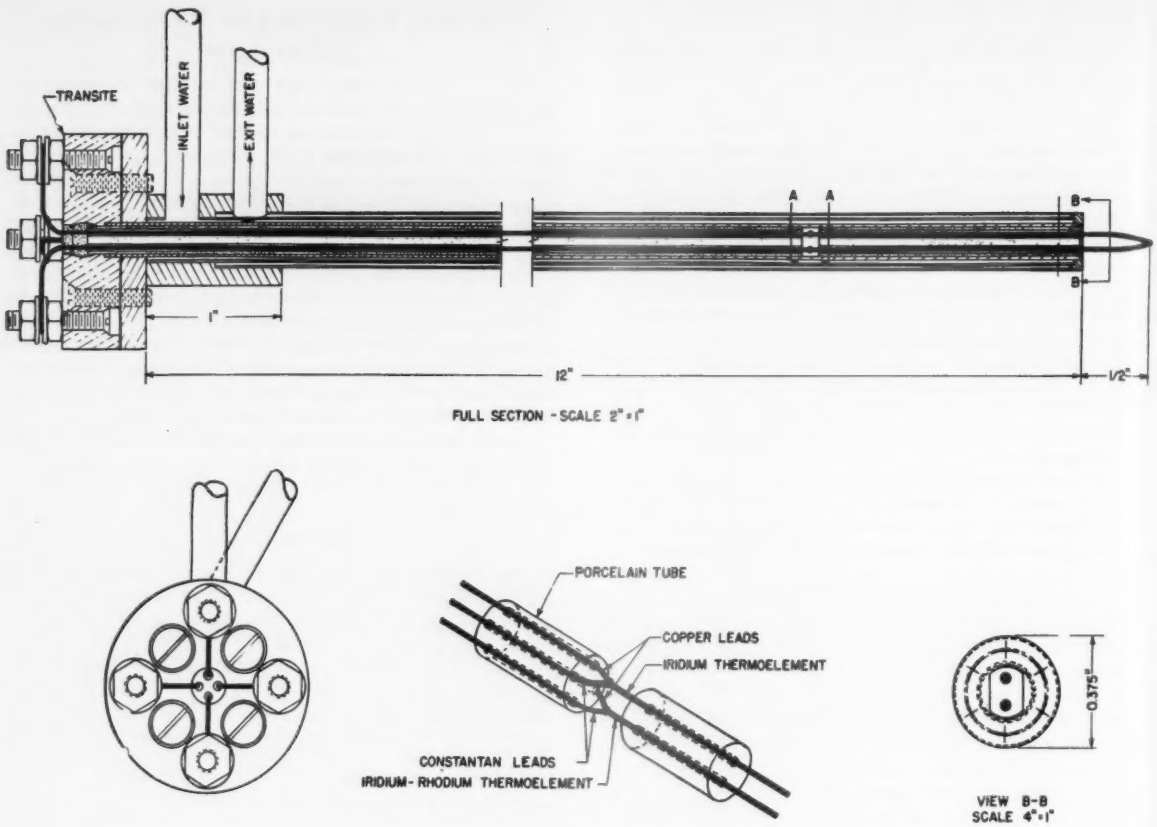

FIG. 3 IRIDIUM-IRIDIUM RHODIUM THERMOCOUPLE WITH WATER-COOLED SUPPORT

under service conditions, requiring that the wires be large under some service conditions. Larger wires may cause greater conduction error, and always reduce the rate of response. Secondly, it is difficult to prevent disintegration of the insulating material at the region where the thermoelements emerge. Thirdly, under conditions of severe vibration, grinding action will occur if the wires are free to move within the insulation, as is the normal situation with wires inserted in a two-hole porcelain tube. Wires have often been completely severed in this way, particularly at the end or at a break in porcelain tube, both in engines and in the laboratory. Probably the best solution now available for base metal thermocouples is the use of swaged magnesia insulation, the magnesia being packed tightly and uniformly within the outer supporting tube and around the wires, thus preventing relative movement. The means used to prevent chipping of the swaged magnesia where the bare wires emerge are not known to the authors, but commercial units seem to be generally satisfactory in this respect.

Thermocouples of Pt-PtRh have not been used widely in exhaust gas because of high initial cost, the possibility of harmful contamination by sulfur, lead, and silicon, the relatively low thermoelectric power, such softness at elevated temperatures that wires are bent at moderate gas velocities, and catalytic surface action which is known to occur at temperatures below about 1200°F. Nevertheless, such thermocouples are the only ones for which standard calibration data are available in the range between 2200° and 2650°F, and their use within a protecting sheath is feasible.

The equilibrium combustion products of maximum power mixtures of hydrocarbons and air attain a peak temperature of about 3500°F when the constituents approach the flame at approximately room temperature. Initial heating during compression of the air raises the final temperature somewhat. Since such conditions may prevail in afterburners and in ramjets, the development of thermocouples useful to 3500°F and above is of considerable practical importance. These temperatures not only exceed the melting points of common metals and alloys, but are so high that they cause common insulating materials such as porcelain to become conducting. The development of high-temperature thermocouples thus involves a search for suitable thermoelements and for satisfactory means for mounting and insulating them.

Tungsten, tantalum, molybdenum, and some of their alloys have sufficiently high melting points and mechanical strength. It is probable also that combinations with usable thermoelectric properties exist. However, these metals oxidize readily and can even be burned at high temperatures. Hence their use as bare thermoelements must await the development of satisfactory protective coatings, which, so far as is known to the authors, is still far in the future.

Among the noble metals melting above 3500°F are iridium, rhodium, and certain alloys of these. Fuessner (5) reported that a thermocouple of Ir and 40 per cent Ir-60 per cent Rh was satisfactory up to 3650°F. More recent studies at the National Bureau of Standards with materials of unknown purity confirm this conclusion and indicate also that the exact composition of the alloy may not be critical. Since the available materials were not of thermocouple quality as to composition or structural uniformity, no standard calibration curve could be developed. However, a commercial source of thermocouple-grade materials is now in prospect, and a standard

calibration curve for representative samples of the lot, which is currently being reduced from ingots to wire, will be determined in the near future. The producer expects to be able to make other lots having identical thermoelectric properties, as the demand develops.

Although these materials are too brittle for sharp bending at any temperature, they appear to be very strong at 3500°F if the elastic limit is not exceeded. They are very expensive, the impure materials costing approximately ten dollars per double inch, i.e., for one inch of thermocouple. The thermoelectrical power is far less than could be desired, and corrections for radiation loss or means for its reduction remain to be worked out. Nevertheless, thermocouples of uncontrolled composition have proved very useful, after individual calibration, in a variety of combustion studies.

The authors have developed mounting means which are satisfactory, at least for some applications. One of these, suitable for laboratory use, is the water-cooled support tube shown in Fig. 3. In these experimental units, thermoelements 0.03 in. in diameter extend from the junction to points about 2 in. within the cooled support. There they are soldered or brazed to Cu-Kn thermocouples, which are used for measuring the reference junction temperature of the noble metal couple. The Cu leads are used when the emf of the Ir-IrRh junction is observed. Experience with these units indicates that, with a copious supply of cooling water, measurement of its initial temperature suffices as the reference junction temperature of the Ir-IrRh couple, so that only the copper leads are really necessary.

Units of the type shown in Fig. 3 have been used in a variety of ground tests. Indicated temperatures have ranged up to 3750°F, and the gas velocities varied up to sonic at about 3500°F. In one installation, operation was satisfactory for a total of 14.5 hours at an average gas temperature of 3600°F.

The desirability of an uncooled support for flight application is obvious. Some progress has been made in this direction by using a silicide-coated molybdenum support tube and a two-hole insulating tube of pure thoria. From purified thoria powder supplied by the National Bureau of Standards, these experimental insulating tubes were made without cost by the American Lava Corporation, whose cooperation is gratefully acknowledged. The insulation resistance of such tubes is high, even while immersed in flame at 3500°F. In the uncooled units the thermoelements must be long enough to extend to a relatively cool region in which they are attached thermally, but not electrically, to metal blocks serving as the reference junction whose temperature is measured by conventional means. Such a unit has been used without apparent damage for a total of about 30 hours in a gas stream where it frequently indicated temperatures as high as 3000°F. None has been used in engines, and their ability to withstand continued vibration is questionable.

Thermocouples may be completely encased in sheaths which are more resistant to corrosion and stronger mechanically than the thermoelements themselves. An insulated thermocouple may be completely sheathed, or, in the so-called pencil-type unit, the outer tube is one of the thermoelements, usually Ch because of its favorable stability. A coaxial Alu wire is welded to the Ch tube at its tip to form the measuring junction. When used singly, units of this type may be grounded at one location. However, for use in parallel, as is usual in turbojet engines, they must either be insulated completely from the ground, or the thermoelements must be insulated from other parts of the thermocouple. For example, the measuring junction may consist of a short length of small, finned Ch tube welded to a coaxial Alu wire, this assembly being mounted in the end of a metal support tube by means of ceramic bonded to both. The difficulty of producing such insulating bonds capable of withstanding severe vibration at high operating temperatures is obvious.

As compared with bare base-metal thermocouples, sheathed and pencil-type units may have greater strength and resistance to corrosion, but they have the same radiation problems and are normally much slower. Attempts to increase their rate of response introduce serious problems of insulation unless a ground can be tolerated.

Coaxial Radiation Shields. Radiation shields consisting of coaxial tubes (6) are widely used and quite effective in reducing the loss of heat by radiation from a centrally located measuring junction. When made of heat-resistant alloys such as stainless steel or Inconel, these shields are useful to a temperature of about 2200°F for extended periods. Silicide-coated molybdenum and certain ceramic materials capable of withstanding the thermal shocks to which they may be subjected are useful to still higher temperatures. However, shielding of this type is heavy and bulky and is seldom used in engines because of space limitations, disturbances to flow, and pressure loss created by the measuring instrument itself at high flow rates.

Radiation Shields of Low Surface Emissivity. Another method of reducing radiation loss is to surround the measuring junction with a shield having a low surface emissivity (7). For example, if an oxidized Ch-Alu junction having an emissivity of about 0.85 is surrounded by silver or gold, either of which has an emissivity of about 0.05, the radiant heat loss is reduced to about one seventeenth that of the bare junction. The shield itself must not make electrical contact between the thermoelements at any point except the junction itself, so that direct plating cannot be used.

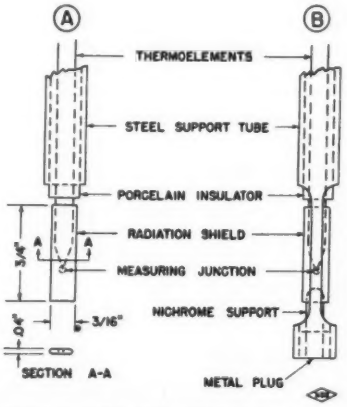

FIG. 4 THERMOCOUPLES WITH PRESSED RADIATION SHIELDS

A practical method of making what may be called a pressed-shield junction is illustrated in Fig. 4(A). The bead of a conventional welded junction is filed to the form of a disk having a thickness about equal to the diameter of the wires. A $^3/_4$-in. length of fine silver, gold, or platinum tube is flattened so that it will slip freely over the disk and the wires. After the disk and about $^1/_2$ in. of the adjoining wires have been oxidized by heating to a dull red in a mild air-gas flame, the disk is inserted to the approximate center of the flattened tube. The flattening of the tube is then continued in a press or vise until the junction is held firmly by the tube, which becomes about 0.2 in. wide and 0.04 in. thick when No. 22 gage wires and $^1/_8$-in. × 0.02-in. tube are used. Such a shielded junction is simple to construct, reasonably rugged, and has small physical dimensions, so that it is easy to install; it creates little disturbance to flow, and it responds rapidly to sudden changes in temperature.

Pressed shields of silver or gold are fully as effective as four coaxial tubes of base metal. The upper limit of applicability is about 1600°F for silver shields and about 1800°F for gold shields, because these metals melt at temperatures only a little higher. For still higher temperatures, platinum may be used, but it is only about one fourth as effective as silver or gold. Platinum-shielded junctions should not be used in pro-

ducts of combustion below 1200°F because of reactions catalyzed at the Pt surface.

Where greater mechanical strength is required of a pressed-shield junction, the expedient shown in Fig. 4(B) has proved effective. Additional support is provided by inserting a loop of Ch or Nichrome wire in one end of the partially flattened shield tube and pressing the shield around both the thermocouple and this loop. The loop is then supported by passing its ends through appropriate holes in a plug in the extreme end of the guard tube.

A wealth of satisfactory service experience has been accumulated with pressed-shield junctions in gas turbines, turbojet combustors, and various laboratory test rigs. It has been found that the emissivity of the shields does not change significantly as a result of heating or of deposits. The accelerating effect of silver shields on the corrosion of Alu in sulfurous atmospheres has already been mentioned. This effect has not been noted where the fuel was gasoline or the kerosene-like hydrocarbons used in aviation gas turbines. Apparently the sulfur content of these fuels is too low to produce a significant effect. However, with fuels containing more than 0.1 per cent of sulfur, the deleterious effect is soon apparent. It is noteworthy that this effect is more rapid in the presence of pressed shields than it is for bare thermocouples.

In one test rig for subjecting turbine blades to repeated thermal shock at peak temperatures approximating 2000°F, both bare and Pt-shielded Ch-Alu thermocouples have shown unexpectedly short life. In this case the Ch element disappears near the junction as though it had been dissolved in acid, leaving tapered points where separation finally occurs. The shield seems to retard the process slightly, so is not considered to be a contributing factor. Without positive proof, it is thought that the rapid and extreme temperature cycling may cause flaking of the chromium oxide which normally adheres and protects the alloy from further oxidation.

Thermocouples Aspirated to Subsonic Velocities. Another method of reducing radiation loss is embodied in aspirated units (2a, p. 530; 2b, p. 805) in which gas, whose temperature is to be measured, is made to flow over the measuring junction at a greater subsonic rate than would be the case if the junction were in the free stream. Some radiation shielding is inherent in such an instrument, since the junction must be surrounded by something in order that the flow rate over it may be increased. Thus aspirated thermocouples are effective because the radiant heat loss is decreased by the shielding, the heat supplied by convection is increased by the greater mass flow, and the heat loss by conduction in minimized by the flow of hot gas along the thermoelements. Such instruments are most advantageous where the free-stream velocity is relatively low, as it may be at certain locations in gas turbines, boilers, and flues. A combined correction for conduction, radiation, and recovery factor can be determined by calibration at a known rate of aspiration. Such calibration corrections are directly applicable in service, provided the same aspiration rate is used in both cases.

A recent example of an aspirated thermocouple, developed at the National Bureau of Standards for use in the products of combustion in steam boilers, is shown in Fig. 5. The measuring junction, surrounded by a thin-walled Inconel tube, is located centrally within the throat of a nozzle assembly which is supported on a water-cooled member so constructed that gas whose temperature is to be measured may be pumped through the nozzle and across the junction before it reaches the cooled parts. Some of the hot gas is also made to flow over the outside of the nozzle, so that it also tends to approach the gas temperature and becomes an effective radiation shield. All uncooled parts of the unit are of Inconel, making it useful to the upper limit of Ch-Alu thermocouples. Identical nozzle assemblies of silicide-coated molybdenum are currently under construction. Ceramic protection tubes and Pt-PtRh thermocouples will be used with these to measure gas temperatures up to about 2800°F.

Under given operating conditions the temperature indicated by such an instrument varies with the aspiration rate. However, the error in the instrument under discussion was found to have a minimum value which remained essentially constant for all flow rates corresponding to pressure drops between the nozzle and the head of from 4 to 12 in. Hg. In this range, the differences between the true gas temperature and the temperature indicated by the thermocouple were: 3° at 1000°F, 13° at 1400°F, and 33° at 1800°F.

Since the supporting member is water-cooled, liquid water condenses from flame gas on its exterior. This condensate must not be allowed to enter the nozzle with the aspirated gas, because it would then make the indicated temperature meaningless. Hence, this type of instrument must be installed in an aspect such that both gravity and the flowing gas will cause the condensate to flow away from the nozzle. If the nozzle is sufficiently higher than the head, the free stream may flow at right angles to the unit.

Thermocouples Aspirated to Sonic Velocity. An adaptation of the instrument just discussed, but suitable for indicating free-

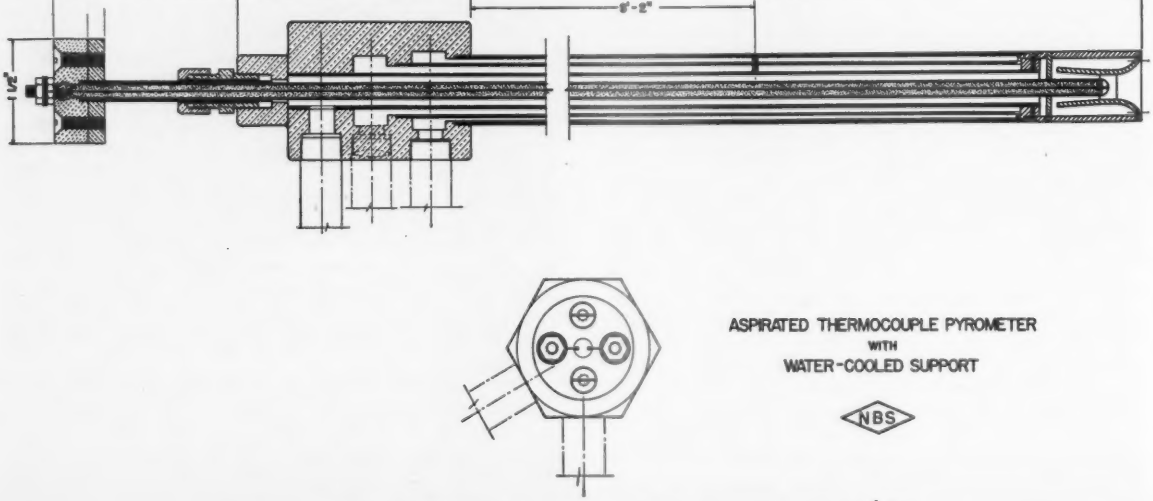

FIG. 5 ASPIRATED THERMOCOUPLE PYROMETER WITH WATER-COOLED SUPPORT

stream total temperature regardless of free-stream velocity, is often referred to as a sonic pyrometer (8). As before, the thermocouple is located in the throat of a nozzle, but in this case the pressure drop across the nozzle is maintained at the critical value, so that the velocity of the gas in the throat is always sonic. Thus the rate of convective heat transfer to the junction is maintained at its maximum possible value.

Assuming the perfect gas law, the sonic velocity V_c of the gas over the thermocouple is given by the equation

$$V_c^2 = \gamma g R T_s \quad [4]$$

in which R is the gas constant and the other quantities have already been defined. Combining Equations [1], [2], and [4] gives

$$T_t = (\gamma_1 + 1)T_i/[2 + r(\gamma - 1)] = \alpha T_i \quad [5]$$

in which

$$\alpha = (\gamma + 1)/[2 + r(\gamma - 1)]$$

If γ and r were constants, calibration and use of the sonic pyrometer would be quite simple. It was expected that the recovery factor of a bare junction located in a sonic stream and obstructing only a small fraction of the flow area would approach the theoretical value for a flat plate (9), which is about 0.87. Lalos (8b) has shown that this is the case, so that the α of a given instrument depends primarily upon the γ of the gas passing through it. Between room temperature and 6000°F, the γ of combustion products varies between 1.4 and 1.28, which, for $r = 0.87$, corresponds to a decrease in α of less than 0.6 per cent. Thus a determination of α with air at room temperature, and the subsequent use of this calibration factor at other temperatures should not lead to errors greater than 0.6% of the absolute temperature. Where higher accuracy is desired, α may be determined in a calibration covering the range of conditions to be encountered in actual service.

Not all of the precautions essential to the satisfactory performance of sonic pyrometers have been determined, although some of them have. Considerable care is necessary in the design of the flow passages throughout the entire unit to insure that choking takes place only in the throat of the nozzle. Location of the measuring junction in the close neighborhood of the region of sonic flow is highly desirable. Certainly its axial position must remain unchanged between calibration and actual use. A stagnation chamber ahead of the nozzle appears essential if the instrument is to be insensitive to free-stream velocity. The presence of such a chamber counteracts some of the gain in response rate produced by the high flow rate over the junction. Further research and development are in progress to clarify effects of the size and shape of both nozzle and measuring junction, and to attain improved mechanical stability. Although the experimental units studied by Lalos (8b) were found to be essentially free from radiation and conduction effects, and to be independent of free stream velocity, these are not suitable for use in engines.

Total-Temperature Probes. Since the total temperature of a flowing gas is the temperature it would have if brought to rest reversibly and adiabatically, it can be measured by locating a temperature-sensing element within a properly designed stagnation chamber. As with the suction pyrometer, some shielding from radiation is provided automatically in accomplishing the deceleration. Free-stream gas enters a cavity through an upstream opening, and its directed velocity is converted into random molecular motion. The outermost surface of the stagnation chamber also decelerates the free-stream gas, but does not bring it completely to rest, so that this surface attains a temperature intermediate between the free-stream T_s and T_t. The stagnation chamber may also lose heat to the surroundings by radiation and conduction. Heat therefore tends to flow from the stagnant gas within to the outer wall of the stagnation chamber, thus reducing the temperature of the stagnant gas. The ability of a total-temperature probe to indicate true total temperature, and thus have a recovery factor of unity, depends primarily upon how well the effects of heat loss can be overcome by design.

There is some gain to be had by proper shaping of both exterior and interior parts of the stagnation chamber, but even greater benefit is produced by downstream bleeding. In this way the decelerated gas is replaced continuously and most of the heat leak to the surroundings comes from gas near the walls, while that bathing the thermocouple remains at T_t. Obviously the rate of bleeding must be limited and the velocity through the stagnation chamber kept low enough that T_s and T_t are nearly equal.

Total-temperature probes having recovery factors very close to unity (10) have been developed for use in wind tunnels and other laboratory equipment. However, the severity of operating conditions and the space limitations in engines make complex units with very high recovery factors undesirable, and favor use of simpler, more rugged units with somewhat less recovery. Units suitable for use in engines are simply bare thermocouples with guard tubes extending beyond the measuring junction. The bottoms are normally closed, and gas which enters through an upstream opening below the junction flows slowly across it and out through a smaller hole in the opposite side. Best performance is attained when the area of the inlet is about ten times that of the outlet. Such a unit usually has a recovery factor in the range 0.9 to 0.97. Its characteristic time is considerably greater than if the junction were exposed to the free stream because of the lower flow rate in the stagnation chamber. However, the radiation correction is normally less than that of a bare junction because the guard tube acts as a shield.

Resistance Thermometers

For several reasons, resistance thermometers (2c, p. 8) are seldom used in engines, even though they can be far more precise instruments than thermocouples. Rugged construction is difficult to achieve, and a resistance coil is larger than a thermocouple. Contamination of the resistance element has a much greater effect upon the calibration than in the case of a thermocouple, so that a protecting sheath is required for a resistance thermometer. Both the rugged mounting means and the sheath contribute to making the response rate slower than for bare thermocouples. Factors favoring the resistance thermometer are that it can be highly accurate, that no reference temperature is required, and that, when used with an a-c bridge, the output signal is more readily used for actuating controls than the d-c output of a thermocouple.

The most common resistance elements are platinum and tungsten. Wire of these materials may be supported and protected by embedding in quartz or other ceramics. Protection may also be provided in sheathed units by surrounding the resistance element with an inert or a reducing gas.

The use of resistance thermometers at high temperatures involves the problems of heat exchange already discussed for thermocouples.

Thermistors

A thermistor (contraction of thermally sensitive resistor) is a form of resistance thermometer whose sensitive element is a semi-conducting material having a high negative coefficient of resistance (2c, p. 8). Thermistors can be fabricated in any desired size or shape by pressing and sintering mixtures of metallic oxides. The principal problem in developing a useful unit is to find a mixture which, after such preparation, has both an appropriate temperature coefficient of resistance and a stable calibration. Attachment of leads also requires special techniques. These problems have been solved for units useful in the approximate range from −150° to 600°F, and thermistors of several types are in general use within this range as thermometers, bolometers, controllers, etc. Dowell (11) lists 40 references on thermistors and their applications.

As a first approximation, the logarithm of the resistance of a thermistor varies as the reciprocal of its absolute temperature, or

$$\log R = a + b/T \quad [6]$$

in which a and b are constants which can be determined by measuring the resistances at two known temperatures. In the most favorable range the temperature coefficient of resistance ($dR/RdT = -b/T^2$) may be as great as -0.03 ohms/ohm °F. The corresponding value for a platinum resistance thermometer is 0.00218. When heated from 32° to 212°F, the resistance of a typical thermistor decreases to roughly one thirtieth the value at the ice point, while that of a platinum thermometer increases less than 40 per cent over the same range.

Even though the problems of developing thermistors stable at high temperatures and of making sturdy mountings and contacts for them have not been solved, it would seem unwise to eliminate units of this nature from future considerations involving high-temperature applications.

Heated-Wire Method

The use of an electrically heated wire for measuring gas temperature was suggested by Berkenbusch (12a) and tried later by Schmidt (12b) and by Griffiths and Awbery (12c). Suppose that a wire (or other appropriate resistance element) is provided with current and potential leads and installed in a vacuum, so that it is subject to no heat exchange by convection. At known values of heating current I, its temperature T is measured by an optical pyrometer and its resistance R by a bridge. The temperature measurement requires knowledge of the surface emissivity of the wire and of the absorption of the window through which the pyrometer is sighted. The resulting R-T relationship constitutes a calibration of the wire as a resistance thermometer. At every point on the I-T curve, the I^2R loss across the wire is equal to the total heat loss by conduction and radiation.

The unit is next placed in a hot gas stream and a new I-R curve determined. The corresponding I-T curve can then be derived from the previous calibration. If the total loss by conduction and radiation at any given wire temperature is the same in the two experiments, the I-T curves for the two cases will intersect at the gas temperature, since this is the only point on the curve applying to the hot gas where there is no convective transfer. There must be no appreciable radiation from the flame to the wire.

The practical difficulties of making the conduction and radiation loss more or less identical under two sets of widely different experimental conditions, of achieving adequate mechanical strength, and of avoiding contamination and possible surface reaction severely limit the usefulness of the method, particularly in engines.

Optical and Radiation Pyrometers

Since products of combustion normally have a low emissivity, their temperature cannot be measured by sighting either an optical (2c, p. 9) or a radiation (2c, p. 10) pyrometer on the gas itself. Hence the use of such instruments for the measurement of gas temperature requires that an opaque target be brought to the gas temperature, so that it may radiate to the sensing instrument. Relatively large targets are required, and it is obviously more difficult to bring a large target to the gas temperature than it is to bring the junction of a thermocouple to this same temperature. For this reason, together with others which need not be enumerated here, the use of optical and radiation pyrometers is not recommended for the measurement of temperature in high-velocity high-temperature gas streams.

Thermodynamic Systems

There have been investigations of various systems whereby gas temperature may be calculated from other measured properties and from known thermodynamic behavior during flow through nozzles and orifices. Such systems are largely independent of the troublesome effects of heat transfer which burden the systems described heretofore. There is also a possibility that the range of thermodynamic systems may be extended beyond the melting points of common metals by careful use of external cooling means.

No attempt is made to include here all the thermodynamic systems which might provide data for calculating gas temperature, nor to trace any such system to its obscure original conception. Rather, this discussion is limited to those systems which have been involved in recent attempts to develop practical instruments. The authors feel that no such instrument is yet ready to use with confidence in an operating engine.

The systems of present interest are basically alike in that all involve flow of the gas whose temperature is to be measured, through two constrictions in series. These constrictions may be either nozzles or orifices, in whatever combination seems desirable for the application. Passage of the gas through both constrictions must be adiabatic, and between them there must be no change in either the number of molecules or in the total mass of gas. In other words, neither condensation, continued reaction, nor leakage can occur between them. However, the principal virtue of such systems is that the pressure and temperature (and hence also enthalpy) of the gas may be changed as desired between the constrictions. Thus the temperature and velocity of the gas, which may be high and difficult to measure at the first constriction, may be reduced at the second one to values which can be measured with ease.

System A (Ref. 13). Consider that the first constriction is located in a stream of hot gas whose temperature is of interest, and that, within the limitations just cited, the gas is cooled to a moderate temperature still above its dew point by the time it reaches the second constriction. Designating static pressure as P_s, pressure drop across a constriction as ΔP_s, density as ρ, and using the subscripts 1 and 2 to designate the entrances to the two constrictions, then by continuity

$$K_1\rho_1\Delta P_{1s} = K_2\rho_2\Delta P_{2s} \quad [7]$$

in which K depends upon the physical and the flow characteristics of the constriction, primarily its coefficient of discharge and area A. Over a considerable range of subsonic flows the coefficient of discharge is sensibly constant, as is K in this same range.

Assuming that $\rho = P_s/RT_s$, Equation [7] reduces to

$$\frac{T_{1s}}{T_{2s}} = \frac{P_{1s}}{P_{2s}}\frac{\Delta P_{1s}}{\Delta P_{2s}} \times \text{const} \quad [8]$$

Obviously T_{1s} can be calculated from observed values of pressure, pressure drop, and of T_{2s}, provided the constant of proportionality is known from a calibration.

In an effort to reduce the number of measurements required, More (10c) suggested the use of two automatic controls on the second orifice. One is a pressure regulator for keeping ΔP_{2s} constant, and the other is a needle valve so actuated by a bimetallic strip that the area A_2 of the second orifice is changed with T_{2s} in such a manner that the ratio $A_2/T_{2s}^{1/2}$ is kept constant. If these controls perform as specified, Equation [8] for the system reduces to

$$T_{1s} = P_{1s}\Delta P_{1s}/P_{2s} \times \text{const} \quad [9]$$

If an instrument is built and operated in such fashion that both ΔP_{1s} and the line loss between the constrictions are small in comparison with P_{1s}, the ratio P_{1s}/P_{2s} remains essentially constant and equal to unity, so that Equation [9] becomes simply

$$T_{1s} = \Delta P_{1s} \times \text{const} \quad [10]$$

After the constant is determined by calibration, a pressure gage, for indicating the drop across the first constriction,

may be graduated to read the gas temperature directly.

Of the automatic controls for maintaining ΔP_{2s} and $A_2/T_{2s}^{1/2}$ constant, none available to the National Bureau of Standards have been trouble-free. To further investigate the system, the automatic controls were therefore eliminated. Using a fixed-area second orifice, the pressure drop across it was controlled manually, and T_{2s} was maintained at approximately 212°F by immersing this orifice and some of the line leading to it in actively boiling water. Measured values of free-stream temperature in the range 100° to 1600°F were reproducible and in good agreement with values measured by other methods so long as the free-stream velocity was low. As this was increased above 100 ft/sec, the effect of free-stream velocity became increasingly significant. Further study of this velocity effect is in progress.

The possibility of cooling the first constriction has also been investigated. The most important result of this study is that carbon is deposited on the constriction when it is cooled too much. The alternate formation and flaking-off of such deposits cause random changes in the effective area of the constriction which make the calculated values of gas temperature erratic. Some cooling without impairing the performance of the instrument appears practicable, but the exact limit is difficult to determine because the temperature of the inner surface, where the harmful deposits may occur, cannot be measured accurately.

System B. Wildhack (14) describes several possible applications for series constrictions in which critical flow is maintained across both. The establishment of critical flow means that one more thermodynamic equation, i.e., Equation [4], becomes applicable in the derivation of equations relating the various pressures and temperatures. Reference (14) contains such equations applicable for all possible combinations of nozzles and orifices, and points out that nozzles require less pumping effort at the high flow rates involved.

Blackshear (15) describes an instrument having two orifices in series, the one in the hot gas being water-cooled. After calibration, the performance of the unit with critical flow through both orifices was studied by direct comparison with a shielded thermocouple in the range 250° to 700°F, and with line-reversal temperatures in the approximate range from 2940° to 3540°F. Agreement in the low-temperature range was excellent; that in the high range was within about 2 per cent, some of the difference being due to uncertainties in the spectroscopic values.

System C. Clark and Rohsenow (16) have developed a thermodynamic method and made a preliminary evaluation of a laboratory instrument for measuring the static temperature of flowing gas. This system, shown schematically in Fig. 6, consists essentially of a water-cooled probe with an opening pointing directly upstream, having a static pressure tap near the opening and a Pitot tube in its axis. The flow rate through the opening is adjusted by a valve at the pump and measured by means of a downstream calibrated orifice located after a heat exchanger in which the gas has been cooled to a temperature convenient for measurement. The static temperature of the gas just inside the opening to the probe is calculated from the equation

$$T_{1s} = \frac{2g}{R_1}\left(\frac{P_{1s}}{G_1}\right)^2\left(\frac{\gamma}{\gamma-1}\right)\left[\left(\frac{P_{1t}}{P_{1s}}\right)^{(\gamma-1)/\gamma} - 1\right] \quad \ldots [11]$$

in which the subscript 1 refers to conditions just within the opening of the probe. If the mass flow rate G_1 through the instrument is adjusted so that the static pressure within the probe is equal to that of the free stream in the same transverse plane, then the stream tube entering the probe neither expands nor contracts externally, and the state of the gas is the same within and outside the probe. Under these conditions the T_{1s} of Equation [11] is identical with the free-stream static temperature. Since it was impossible to locate a static pressure tap within the probe exactly at the opening, the probe tested indicated free-stream temperature when the static pressure at the internal pressure tap was higher than that of the free stream by about one inch of water. Determination of this pressure difference required for optimum performance of a given unit may be regarded as one step in its calibration.

It was shown that the value of T_{1s}, obtained from Equation [11] by inserting the observed pressures and mass flow rate, is largely independent of γ, since the influence of the factor $\gamma/(\gamma-1)$ tends to counteract that of the exponent $(\gamma-1)/\gamma$. At low velocities, changing γ has no appreciable effect on T_{1s}, and at sonic velocity the changes in γ common to combustion products would affect T_{1s} to the extent of only about 1 per cent of its absolute value.

The results also show the effects upon T_{1s} of failure to adjust the velocity through the opening of the probe to equality with that in the free stream. Free-stream total temperature can also be calculated from the observed quantities, but for this purpose a knowledge of the composition of the gas is required in order that an accurate value of γ be known.

Indirect Thermodynamic Methods. Upon occasion it is expedient to calculate the temperature of combustion products from other measured quantities. One such method involves analysis of the products, from which the heat liberated by the reaction is calculated. A heat balance equation may then be set up and solved by successive approximations. Recourse must be had to reference tables of heats of formation and enthalpies of reactants and products. Temperature calculated in this way depends greatly upon obtaining a representative sample whose composition is unchanged during passage through the sampling device and upon the accuracy of the analytical results.

Another indirect method, involving a so-called pressure-sensitive system, has been described by Cesaro and co-workers (17). Gas temperature after combustion is calculated from such measured quantities as inlet air temperature, fuel/air ratio, certain dimensions of the burner, and various total and static pressures. Agreement of temperatures obtained in this manner with values obtained by thermocouples was within ±2 per cent.

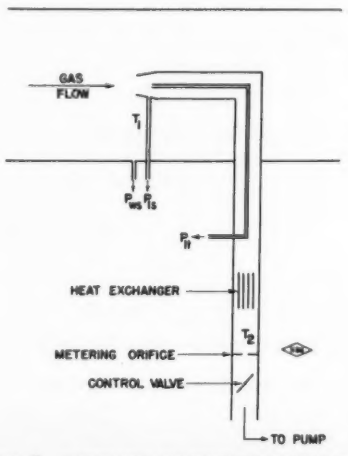

FIG. 6 SCHEMATIC DIAGRAM OF SYSTEM C

Thermal Noise Thermometer

Garrison and Lawson (18) describe a temperature-sensing instrument based upon the random thermal noise which exists in an electrical circuit through which no steady current is flowing, the mean-square voltage fluctuations over a range of frequencies being directly proportional to the absolute temperature. Primarily because the characteristics of amplifier and detector tubes vary with time, the ratio of two absolute temperatures can be determined by this method with higher

accuracy than either can be determined individually. Although it seems improbable that the noise thermometer will be developed to the stage where it can be used in engines, it is still being investigated as a possible means of establishing a more accurate scale of absolute temperature in the range of interest in power plants.

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Optical Methods for the Determination of Combustion Temperatures[1]

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A brief survey is presented of optical methods for the determination of temperatures which can be used in rocket engines. The data are presented in outlines and include an outline of basic principles involved in application of a given technique, a sketch of the experimental arrangement, and key references which should be consulted for further details.

Nomenclature

α_1, α_2	= known proportionality constants
c_1	= first radiation constant = 3.74×10^{-4} (erg-cm²)/sec
c_2	= second radiation constant = 1.432 cm-°K
c	= velocity of light
ϵ	= total energy of initial quantum state
ϵ_{el}	= electronic energy of initial quantum state
ϵ_{rot}	= rotational energy of initial quantum state
ϵ_{vib}	= vibrational energy of initial quantum state
ϵ_λ	= average emissivity for the wave-length range between λ and $\lambda + \Delta\lambda$
I	= total intensity of a spectral line
i	= transition probability
$J(\lambda, T)$	= radiant intensity emitted by a blackbody at wave-length λ and temperature T
k	= Boltzmann constant
λ	= wave length
m	= mass of a molecule
ν	= frequency
R_λ	= average reflectivity for the wave-length range between λ and $\lambda + \Delta\lambda$
T	= absolute temperature
T_F	= flame temperature
T_{br}	= brightness temperature of a flame
T_{Sbr}	= brightness temperature of the light source used in reversal experiments
T_c	= color temperature of a flame

I INTRODUCTION

OPTICAL methods for the determination of temperatures have the unique advantage of permitting experimental observations without disturbing the system being studied. On the other hand, they usually involve averages over the field of view and are therefore incapable of yielding point functions for physical variables. Extensive applications of spectroscopic techniques have been made only to temperature measurements on laminar flames for premixed gases, although some studies have been reported also of temperatures, pressures, and velocities for rocket exhaust gases and for liquid- and solid-propellant combustion chambers.

Since review articles are available on the general subject of optical methods for measuring flame temperatures, a recent and extensive survey being one published by Penner in 1949 (1),[4] it does not appear to be necessary to emphasize historical development and to attempt a complete literature review. Rather, we shall content ourselves with summarizing basic principles, with an outline of experimental arrangement, and with a set of key references denoted by (*a*) if referring to one of the earliest applications of the method, designated by (*b*) if containing an adequate review of basic principles and of some of the work done in the field, and identified by (*c*) if dealing with a recent example of good experimental technique. Many significant references have been omitted in this survey, but those quoted should be sufficient to lead the interested reader to more extensive compilations of the literature. For a listing of references on jet propulsion research, a compendium published recently by the National Bureau of Standards may be consulted (2).

The subject of measurements of temperatures for isothermal and for nonisothermal emitters is surveyed in the following Sections II and III, respectively.

II OPTICAL METHODS FOR MEASURING TEMPERATURES FOR ISOTHERMAL EMITTERS

From the operational point of view, there are as many different "temperatures" in flames as there are measuring techniques. However, experience has shown that the numerical values of a valid temperature determination approach but never exceed the adiabatic flame temperature, provided measurements are made on quantities which are in equilibrium with the random translational energy distribution of the molecules. We may regard a value of the temperature determined under equilibrium conditions as a direct measure of combustion efficiency. In practice it may prove to be exceedingly difficult to eliminate all instances of nonequilibrium excitation. For this reason it is preferable to make temperature determinations by several independent methods rather than to assume that any one procedure leads to a significant approximation to the flame temperature. If two or more independent experimental techniques lead to the same numerical result, then it is very likely that the true flame temperature (defined through the random translational speed of the gas molecules) has been measured.

It is reasonable to consider that unequivocal experimental evidence of "temperatures" exceeding the adiabatic flame temperature indicates departures from equilibrium. If the existence of such abnormal "temperatures" can be established, valuable information may be obtained regarding some of the individual steps in the combustion processes. On the other hand, it is clear that the rocket engineer performing a temperature measurement in order to learn something about the average state of combustion or about the combustion efficiency, will be interested in experimental procedures which measure the average combustion efficiency rather than nonequilibrium distributions of an excited chemical species whose role in the combustion reactions may be only of academic significance.

A summary of optical methods for measuring temperatures of isothermal emitters is given in the following sections. The remarks at the end of each section contain recommen-

[1] Supported by the ONR under Contract Nonr-220(03), NR 015-210.

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[4] Numbers in parentheses refer to the References on page 169.

dations relating to the use of the method, and are based on the results of available practical experience.

1 Determination of Brightness Temperatures

Principles

The brightness temperature T_{br} at the wave-length λ is defined[5] as the temperature at which the emitter under study emits the same spectral intensity of radiation as a blackbody. Thus $c_1\lambda^{-5}[\exp(c_2/\lambda T_{br}) - 1]^{-1}$ equals the measured intensity at λ. The brightness temperature T_{br} is related to the actual temperature T_F of the emitter by the relation

$$(1/T_F) - (1/T_{br}) = (\lambda/c_2) \ln \epsilon_\lambda \quad [1]$$

provided an average emissivity ϵ_λ can be assigned to the emitter for the wave-length region to which the pyrometer responds.

Experimental Procedure

An optical pyrometer is suitable for measuring the brightness temperatures of flames. The wave-length region is selected by a filter. A pyrometer compares the brightness of the source with that of a tungsten filament heated to a known temperature.

Remarks

A measurement of the brightness temperature T_{br} can be used to obtain the temperature T only if the emissivity ϵ_λ is known, which is generally not the case. For flames containing solid particles (such as finely divided carbon), the emissivity ϵ_λ may be known or else may not differ greatly from unity. The method is not useful for reacting gas mixtures.

References

(*a*): (3). (*b*): (1). (*c*): Manuals supplied with commercial optical pyrometers.

2 Two-Color Temperatures

Principles

The color temperature T_c of an emitter is defined as the temperature at which a blackbody emits radiation having the same ratio of radiant intensities at the wave lengths λ_1 and λ_2 as the emitter under study. This definition of T_c is expressed by the relation

$$J(\lambda_1, T_c)/J(\lambda_2, T_c) = \epsilon_{\lambda_1}(\lambda_1, T)J(\lambda_1, T)/\epsilon_{\lambda_2}(\lambda_2, T)J(\lambda_2, T) \quad [2]$$

The color temperature T_c is related to the true temperature T through the expression

$$(1/T) - (1/T_c) = \ln(\epsilon_{\lambda_1}/\epsilon_{\lambda_2})/c_2[(1/\lambda_1) - (1/\lambda_2)] \quad [3]$$

if the intensity of radiation emitted by a blackbody may be approximated by Wien's equation, i.e., if $\lambda T \ll c_2$.

Experimental Procedure

The two-color method requires the determination of intensity ratios in emission at two wave lengths. Photoelectric detectors with wave-length filters are useful receivers.

Remarks

The two-color method can be used if emissivity ratios at two wave lengths are known. For flames containing solid particles, it may be possible to calculate or measure emissivity ratios (4, 5), or else it may be justified to assume that the emitter is a greybody, i.e., $\epsilon_{\lambda_1} = \epsilon_{\lambda_2} < 1$.

For homogeneous gases at elevated pressures, the two-color method can be made precise by selecting wave-length regions for which emissivity ratios can be calculated as a function of temperature and pressure. The labor involved in the use of the precise procedure is considerable and no published examples of application are available.

References

(*a*): (4). (*b*): (1), (5), (6). (*c*): (5), (6).

3 Line-Reversal Temperatures

Principles

A thermally excited spectral line may be studied by use of a spectroscope. If the background is not as bright as the flame in a wave-length region including the line center of the emission line, then a bright emission line is observed. On the other hand, if the background is brighter than the flame, the line will appear as a dark absorption line. For a background of arbitrary emission characteristics the emission line merges with the background ("point of reversal") when

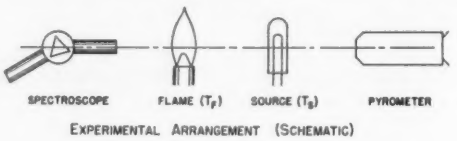
$$T_F = T_{Sbr} \quad [4]$$

where the subscripts F and Sbr identify the true temperature of the flame and the brightness temperature of the background, respectively. It is noteworthy that Equation [4] holds for arbitrary emissivities of the flame.

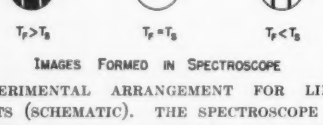
Experimental Procedure

Some of the earliest applications of the reversal method were made to infrared emission bands of H_2O and CO_2, which are normally present in hydrocarbon flames (7, 8). If it is desired to make observations in the visible region of the spectrum, it is necessary to color nonluminous flames by addition, for instance, of sodium salts, which will emit the yellow "D"-lines of sodium.

The experimental arrangement is sketched in Fig. 1. A



EXPERIMENTAL ARRANGEMENT (SCHEMATIC)



IMAGES FORMED IN SPECTROSCOPE

FIG. 1 EXPERIMENTAL ARRANGEMENT FOR LINE-REVERSAL MEASUREMENTS (SCHEMATIC). THE SPECTROSCOPE IMAGES ARE REPRESENTATIVE OF RESULTS OBTAINED FOR THE D-LINES OF SODIUM

small direct-vision spectroscope is suitable for reversal experiments on the sodium D-lines. The brightness temperature of the background is measured with an optical pyrometer.[6]

[5] The phrase "at the wave length λ" is used to summarize the statement "in the wave-length region between λ and $\lambda + \Delta\lambda$" where $\Delta\lambda$ is generally a wide wave-length interval (i.e., of the order of 100 A). For methods 1 to 5 it is advantageous to use a spectroscopic instrument of low resolving power, i.e., to utilize average emissivities over wide wave-length regions. In this case the observations will not be affected significantly by discrete lines.

[6] Recent applications of the line-reversal method for very rapid determinations of flame temperatures have been described by H. F. Quinn ("A Spectrophotometric Determination of Exhaust Gas Temperatures in the Pulsejet Engine," *Canadian Journal of Research*, vol. 28, 1950, pp. 411–432) and by A. Moutet ("Method for Rapid Determination of Flame Temperatures," *La Recherche Aéronautique*, no. 27, 1952, pp. 21–32; no. 28, 1952, pp. 21–30).

Remarks

The method depends on the assumption that the spectral line on which observations are made is excited thermally. This is not necessarily the case. For example, temperatures greatly in excess of the adiabatic flame temperatures have been reported by Gaydon and Wolfhard (9) for the reversal temperatures of iron lines in low-pressure flames. In general, however, the sodium line-reversal method is one of the most convenient and useful methods for temperature determinations in regions of active combustion.

The reversal technique can be extended to cover the case in which the temperature is obtained without requiring precise determination of the point of reversal. This extension has been carried through in the infrared by Silverman (10), and for the OH-bands in the ultraviolet by Curcio, Stewart, and Petty (11).

References

(*a*): (7), (8), (12). (*b*): (1), (9), (13). (*c*): (9), (10), (13).

4 The Two-Path Method

Principles and Experimental Procedure

For a two-path experiment in which the intensities of radiation for a single traversal and for two traversals are measured, let T_{br_1} and T_{br_2} be the corresponding brightness temperatures, and R_λ the reflectivity of the mirror at the wave length λ. The true temperature of the flame T_F is then given by the expression

$$1 - \exp\{(-c_2/\lambda)[(1/T_{br_2}) - (1/T_{br_1})]\} = -R_\lambda\{1 - \exp(-c_2/\lambda)[(1/T_{br_1}) - (1/T_F)]\} \quad [5]$$

if

$$\lambda T \ll c_2.$$

The two-path method is essentially a reversal method in which the source is used as its own background. Two observations of brightness are made, one with a cool blackbody behind the flame, and another with a mirror behind the flame.

Remarks

The two-path method for the measurement of flame temperatures is an optical technique which permits temperature measurements on systems in which the intensity of radiation emitted varies rapidly (and aperiodically) with time. The method is recommended for use whenever spectral emissivity data are not available, i.e., for practically all radiators. This method involves the implicit assumption that the emissivity is a slowly varying function of the wave length in the spectral region at which measurements are made. This assumption becomes apparent if we note that the derivation of Equation [5] involves the use of an average emissivity over the spectral region to which the instrument responds. It is known from experimental studies that the two-path method usually constitutes a very useful experimental procedure for studying the progress of combustion in liquid- and solid-propellant rocket chambers (14).

References

(*b*): (1), (14). (*c*): (14).

5 Compensated Hot-Wire Method

Principles and Experimental Procedure

The temperature of a tungsten wire heated in a vacuum, as determined by an optical pyrometer, will be a function of the power input and consequently of the heating current I (cf curve 1 in Fig. 2). Suppose this wire is placed in a flame of temperature T_F. When the temperature of the wire is below T_F, the wire will be heated by conduction from the hot gases. Therefore, less current will be required to maintain a given temperature in the flame. Above T_F, more current is required than in a vacuum in order to maintain a given wire temperature, since heat is now lost by conduction to the flame. A plot of T vs. I for a wire in a flame gives curve 2 of Fig. 2, which intersects curve 1 at $T = T_F$. At $T = T_F$ there is no heat exchange between the wire and the flame.

Remarks

The method involves the assumption that the wire does not disturb the combustion processes and that its emissivity in the flame is the same as in a vacuum. Although numerous examples of catalytic action by wires in flames have been observed, the compensated hot-wire method is simpler to use than conventional thermocouples and hence is recommended for studies on flames in which point-by-point explorations are desired.

References

(*a*): (15). (*b*): (1), (13), (15). (*c*): (15).

6 Population (Rotational, Vibrational, and Electronic) Temperatures

Principles

The rotational, vibrational, and electronic temperatures are defined through the populations of molecules in different rotational, vibrational, and electronic energy levels. Hence it is appropriate to refer to them collectively as population temperatures.

The intensity of a spectral line depends on the population of the initial state involved in a transition and also on the transition probability. If the energy levels of the initial states are populated in accord with the Boltzmann distribution law, then the intensity of absorption lines, I_{abs}, and of emission lines, I_{em}, are given by equations of the form

$$I_{abs} = \alpha_1 i_1 \nu_1 \exp(-\epsilon_1/kT_1) \quad [6]$$

$$I_{em} = \alpha_2 i_2 \nu_2^4 \exp(-\epsilon_2/kT_2) \quad [7]$$

where α_1 and α_2 are known quantities for given transitions, i_1 and i_2 are the transition probabilities, ν_1 and ν_2 are the frequencies of the line centers, and ϵ_1 and ϵ_2 are the energies of the initial levels involved in absorption and in emission experiments, respectively. In first approximation the energies ϵ can be represented as the sum of rotational (ϵ_{rot}), vibrational (ϵ_{vib}), and electronic energy levels (ϵ_{el}). From Equations [6] and [7] it can be shown that

$$-\partial \ln (I_{abs}/i_1\nu_1)/\partial \epsilon_{1,i} = (kT_{1,i})^{-1} \quad [8]$$

and

$$-\partial \ln (I_{em}/i_2\nu_2^4)/\partial \epsilon_{2,i} = (kT_{2,i})^{-1} \quad [9]$$

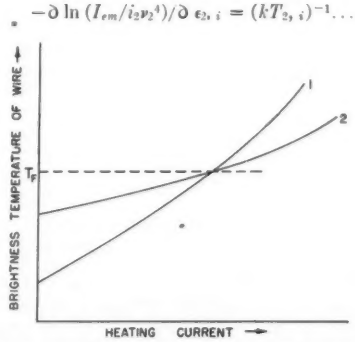


FIG. 2 PLOT OF HEATING CURRENT VS. TEMPERATURE FOR COMPENSATED HOT-WIRE METHOD. CURVE 1 APPLIES FOR A WIRE IN VACUUM. CURVE 2 APPLIES FOR THE WIRE IN A FLAME

where the subscript i may represent either *rot*, *vib*, or *el*. It should be noted that the population temperatures in absorption ($T_{1,\,i}$) and in emission ($T_{2,\,i}$) may be different for a given chemical species.

Experimental Procedure

Well-resolved spectra showing individual spectral lines are, in general, required. In order to minimize temperature gradients normal to the direction of observation, low-pressure flames have been used, particularly by Gaydon and Wolfhard (16, 17).

Remarks

Determination of population temperatures requires elaborate apparatus and has been used most widely for premixed gases and for diffusion flames (18). This method is of primary importance for studies designed to determine combustion mechanism. There has been considerable discussion recently concerning the proper interpretation of experimental data obtained for OH (19–23).

References

(*a*): (24). (*b*): (19), (20), (23), (25). (*c*): (16), (19), (26).

7 Temperature Measurements Utilizing Spectral Line Shape

Principles

The mean translational temperature of individual chemical species can be obtained from a study of spectral line shape. For example, for spectral lines with Doppler contour, the half-width $\Delta\lambda_D$ (i.e., one half of the width of the spectral line for which the spectral absorption coefficient exceeds one half of its maximum value) is related to the temperature, T_F, defined by the random translational motion, through the relation

$$\Delta\lambda_D = (\ln 2)^{(1/2)}(2kT_F/mc^2)^{(1/2)}\lambda_0 \ldots\ldots\ldots [10]$$

where m is the known mass of the molecule under study, and λ_0 is the wave length at the line center.

Experimental Procedure

Methods utilizing detailed spectral line shapes require the use of very high-resolution instruments such as interferometers and echelette gratings.

Remarks

The interpretation of experimental data is greatly complicated by the inevitable temperature gradients present in all flames. The method holds the greatest promise for low-pressure flames in which the spectral line shape is relatively simple. Two-path experiments in the infrared and in the ultraviolet have been proposed recently for the simultaneous determination of temperatures and concentrations.

References

(*a*): (27). (*b*): (20), (27). (*c*): (27).

III OPTICAL METHODS FOR MEASURING TEMPERATURES FOR NONISOTHERMAL EMITTERS

It is impossible to measure flame temperatures in nonisothermal systems by optical methods unless either (a) the temperature gradients are known, or (b) the nonisothermal system can be approximated by two or more adjacent isothermal regions. The few published flame-temperature measurements, in which attempts were made to correct for temperature gradients, all involve the use of simple flame models. Related studies by astrophysicists on systems with continuous temperature gradients have not yet been exploited fully for temperature measurements in flames. The published work on flames is summarized in the following sections.

1 Reversal Temperatures for Nonisothermal Emitters

Principles and Experimental Procedure

Griffiths and Awbery (28) showed that the observed reversal temperature was approximately that of the hot region if light from the reversal background passed first through a cool zone and then through a hot zone. If the hot and cold regions were interchanged, then intermediate temperatures were observed.

Remarks

The conclusions reached by Griffiths and Awbery (28) are applicable only to the system on which observations were made, and cannot be generalized to other flames.

References

(*a*): (28). (*b*): (1), (13), (28). (*c*): (28).

2 Reversal Temperatures Utilizing Measurements of Spectral Line Shape

Principles

Strong, Bundy, and Larson (29) have used an interferometer to study line reversal in nonisothermal systems. They obtained resolving power sufficient to observe the contour of individual spectral lines. Analysis of the experimental data involves the assumption that the nonisothermal system can be described by two adjacent isothermal regions.

In a flame the observed line width is determined by three factors, viz., Doppler broadening, collision broadening, and "absorption broadening" which depends on the concentrations of sodium in the hot and cold regions. In an emission experiment the resultant line contour may have the shapes illustrated in Figs. 3a and 3b. If the line shown in Fig. 3b is studied in a reversal experiment with a high resolution spectrograph, reversal is observed in different regions of the line as the brightness of the background is increased. For a suitable source the central region of the line absorbs light and appears dark, whereas the wings of the line remain brighter than the source, thus producing the contour shown in Fig. 3c.

Strong, Bundy, and Larson suggested that, under low resolution, total reversal would be observed when the sum of the areas A and A′ is equal to the area B (cf. Fig. 3c). The authors calculated the contours of Na lines for various optical densities in the hot and cold zones. These were combined to give the observable contour from which the apparent reversal temperature could be derived. The calculations checked well with the observed reversal temperatures for the two zones whose reversal temperatures and optical densities had been determined separately.

The decomposition of an experimentally determined line contour, of the type shown in Fig. 3c, to yield separate temperatures for the hot and cold regions has not been described. This inversion cannot be performed uniquely.

Experimental Procedure

The experiments carried out by Strong, Bundy, and Larson utilized a Fabry-Pérot interferometer in order to obtain line contours. The apparatus was elaborate and costly. The work is of particular interest in the present context because it was extended (30) to measurements of the velocities and pressures of rocket exhaust gases.

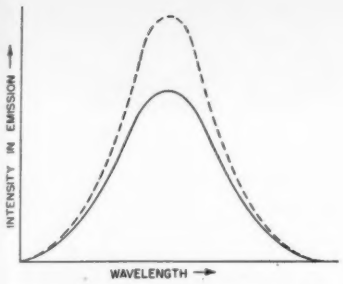


Fig. 3a Emission experiment. The dotted curve represents the emission which would be observed from the hot region alone. The solid curve is produced as the result of absorption of radiation by the cool gas layer

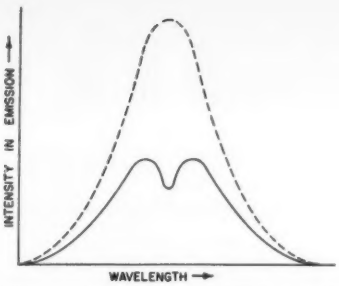


Fig. 3b Emission experiment. The optical density in the cool gas layer has been increased to the point where self-reversal occurs

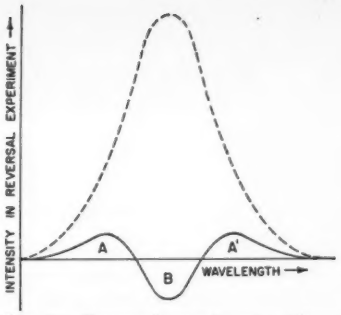


Fig. 3c Reversal experiment. Above the horizontal line the emitted intensity exceeds the intensity of the reversal background; below the horizontal line the converse applies

FIGS. 3A, 3B, 3C CONTOURS OF SPECTRAL LINES OBTAINED WHEN A HOT ISOTHERMAL REGION IS VIEWED THROUGH A COOL ISOTHERMAL GAS LAYER (SCHEMATIC)

3 Population Temperatures

Principles

For flames represented by two adjacent isothermal regions, it is possible to carry through a complete analysis for observable intensities of individual spectral lines (23, 31). Applications of the results to flames have not yet been published.

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Photographic Techniques in Jet Propulsion Studies

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Motion picture photography has become a standard tool for obtaining permanent records of certain phases of jet engine firings. Types of motion picture cameras generally used are discussed here. They have been classified into five categories based on frame frequency or linear film speed. Representative commercially available cameras are reviewed with regard to frame frequency, motor drive, shutter type, special features, etc. Methods generally used to modify test engines to make them amenable to photographic techniques are described. Systems for correlating events with photographs and comments on interpretation of results are presented briefly. A bibliography is appended for the investigator who desires more extensive details.

EVERY investigator has the desire to observe visually the phenomenon he intends to study. Since nature has provided humans with neither sufficiently rapid perception nor an infallible retentive memory, photographic technics have found widespread application throughout all fields of engineering research. Photography has become such a commonplace tool in the analysis and recording of motion that it would be impossible to enumerate and describe in this survey all the techniques that have been devised. Such methods as interferometry, schlieren, and shadow photography have been utilized in diverse fields of investigation. Since a great deal of information is readily available in the literature, no attempt is made to describe them here.

The choice of any experimental technique is based to a large extent on the equipment which is available. Within recent years, a great variety of motion picture cameras have appeared on the market. Before discussing specific examples of commercial equipment, we shall first classify such equipment according to type.

Types of Motion Picture Cameras

Motion picture photography can be classified in five categories, based on frame frequency or linear film speed. These are: normal-speed intermittent, high-speed intermittent, high-speed, very high-speed, and ultra high-speed motion picture photography.

Normal-speed intermittent-type cameras include the standard model movie cameras available on the market and capable of speeds up to 128 frames per sec. These units have intermittent-type film-advancing mechanisms in which the film is in motion only during the time when the shutter is closed. Since the film is stationary during the exposure period, good over-all definition can generally be obtained with this type of mechanism.

High-speed intermittent-type cameras cover the range from normal speeds to 275 frames per sec. Although most of the units which operate exclusively within this range utilize the intermittent-type movement, some of the high-speed rotating-prism type units can operate at 200 frames per sec by reducing the applied voltage. Difficulty may be encountered with the intermittent-type movement at the higher frame rates since high film accelerations are necessary in the interval while the shutter is closed. Jamming of the film and torn sprocket holes are the usual difficulties experienced with this type of movement. Another functional fault sometimes encountered with the intermittent-type camera is the uneven spacing of the frames on the film which results in "jitter" of the image when projected for viewing.

When utilizing the lower range of the high-speed cameras, it is often found that the drive motor has insufficient torque to accelerate the film quickly, and thus an appreciable portion of the film is wasted during the acceleration period. However, newly designed electronic control systems have reduced the acceleration period appreciably. Only 21 per cent of the film is expended in acceleration at all speeds in these apparatus. An example is the Acmade High-Speed Motion Picture Camera.

High-speed cameras, having a range from 275 to 12,000 frames per sec, are available. They usually have a rotating-prism type image movement compensator in which the film is driven continuously and synchronized with the compensator. As the prism rotates, the light rays are refracted in relation to the angle of rotation and the image travels along with the film during the exposure period. Some makes of cameras are equipped with replaceable prism assemblies having different numbers of sides. Doubling the number of sides on the prism doubles the frame frequency and simultaneously reduces the frame height. Although an attempt is made to compensate the prism to prevent differential movement of the image and the film during the entire exposure period, it is impossible to eliminate the aberration altogether; as a result, there occurs a slight blurring of the picture and hence a loss in definition. This fault can be overcome by flashlighting the subject. By synchronizing the flash or strobo light with the shutter so that the flash peak occurs when the prism face is parallel to the film plane, the quality of the picture can be greatly improved. A flash synchronizer is an accessory which can be provided on most of the commercial models of rotating prism cameras. Speed adjustment is obtained by control of the voltage applied to the drive motor.

Cameras capable of frame frequencies in the very high-speed range from 12,000 to 500,000 frames per sec and in the ultra high-speed range above 500,000 frames per sec are, in general, not commercially available but are specially designed and constructed for the particular requirements. Several types are illustrated and described in the literature (14–19).[3] Frame frequencies as high as 10^7 pictures per sec can be obtained with some units. Units with these high frame rates are naturally limited in the total operating time before reloading. Most of these cameras are limited to several hundred pictures total operation.

There is commercially available a unit known as the image converter tube which can be used for both high-frame rate and short-duration, single-exposure pictures. The converter tube itself consists of an evacuated glass envelope with a photosensitive surface (cathode) on one side and a fluorescent screen on the opposite side. The image is focused on the cathode. Electrons are emitted from the cathode, proportional to the light intensity; these electrons are electrically accelerated and focused on the fluorescent screen. The image

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[3] Numbers in parentheses refer to References on page 172.

appearing on the screen can be switched on and off by an electric control signal which functions as a shutter. Image intensification as well as wave-length conversion can be accomplished with this device. Thus a visible image can be produced with the object lighted by ultraviolet light, infrared light, or x rays.

Some techniques, instead of utilizing frame-sequence photography, employ streak or continuous strip cameras (23). Some of the high-speed cameras using the continuously driven film mechanism can be converted to this service by removal of the prism assembly. Other units, as, for example, the General Radio Company Type 651 camera, Fastax Oscillographic camera, and the Warrick Model F camera, are especially well adapted for this purpose. The converter tube image can also be deflected with time-producing results comparable to those of streak or rotating mirror cameras. Continuous strip cameras can be used for intermittent photography of nonluminous events by flashlighting the object.

Available for many of the units discussed above are such features as dual optics for recording simultaneously the event and an oscillographic record, stereophotography optics, narrow and wide angle optics, and event sequence timing devices.

In some investigations an electro-optical light shutter, called a Kerr cell (41), has proved useful. Usually a Kerr cell consists of a parallel plate condenser immersed in a liquid like nitrobenzene and placed between crossed Nicol prisms or polaroids. If the electric field is on, light will pass the combination; but if the field is off, no light can pass through. This shutter, although responding almost instantaneously to electrical control, generally causes a considerable attenuation in the light transmission.

Having discussed the general types of cameras available, several representative commercial models will now be briefly described in order to illustrate the general mode of operation.

Examples of Commercially Available Cameras

Bell and Howell Superspeed Camera (1)

On special order, the Bell and Howell Filmo Model 70S, 16-mm camera, which normally operates at 128 frames per sec, can be supplied with a universal motor drive and modified intermittent-type film moving mechanism with shutter to permit picture frequencies as high as 240 frames per sec. The drive motor is a 24-volt universal type and may be energized with either a-c or d-c; the higher frame frequency is obtained by exciting the motor from approximately 28 volts d-c or a slightly higher a-c voltage. The camera can be supplied to take the 400-ft film magazines. The standard line of lenses for the Filmo cameras is available.

Mitchell High-Speed Camera (2)

The Mitchell High-Speed Camera (intermittent-type movement), available in either 16- or 35-mm models, is designed to operate through the range from 8 to 128 frames per sec, depending on the type of motor drive supplied. For the range from 24 to 120 frames per sec, a 110-volt universal type motor, which can be operated on a-c or d-c, is used. A separate rheostat is used to control the speed. The film magazines which mount on top of the camera are available in either 400- or 1000-ft capacity. One of the features of the camera is a four-lens turret with provisions for focusing through the photographing lens.

Acmade High-Speed Camera (3)

The Acmade High-Speed Motion Picture Camera is a 35-mm camera utilizing a 4-sided removable prism as a shutter in the frame frequency range from 100 to 2000 full-frame pictures per sec. These frequencies can be doubled by inserting an 8-sided prism to obtain half-frame pictures. The camera is equipped with the optics to record simultaneously on the film the event and an associated oscillographic record; a synchronizer is provided to trigger a gaseous discharge tube unit for 5-microsec duration flash illumination of the subject. A 200-ft demountable film magazine is supplied. A control unit, providing for a 21 per cent film acceleration period, contains the rectifier power supply, a film speed control (in 6 finite steps), a 1000-cps time base oscillator, and the trigger amplifier for the flash discharge tube.

Fastax Cameras (4)

Wollensak Optical Company's Fastax is a continuous strip camera available in 8-mm, 16-mm, and 35-mm models. Speeds from 150 to 8000 frames per sec can be obtained with the 16-mm models which utilize a 4-sided prism shutter. Frame rate is varied by controlling the voltage applied to the universal-type film drive and take-up motors. A neon glow lamp, mounted such that it will expose a portion of the film along the edge adjacent to the sprocket holes, is used for timing and event marking on the film. A 1000-cps oscillator can be furnished to drive the neon bulb. A wide assortment of lenses can be furnished for long-range work or wide-angle close-up work. Other accessories available are automatic camera and event timer (Goose Timer), and a stereoscopic attachment. The camera can be supplied without the prism so it may be used as an oscillographic and streak camera. A 500-ft film capacity camera is available in the 35-mm model.

Kodak High-Speed Camera (5)

Eastman Kodak's Camera utilizes a two-sided synchronized prism for taking pictures in the range from 1000 to 3200 frames per sec on 16-mm film (adjustable at the camera itself). By reducing the applied voltage, speed may be reduced to as low as 300 frames per sec. Either alternating or direct current can be used. An event timer and camera-shutdown device are synchronized to the film drive mechanism so that their operation is determined on a footage basis. An argon timing lamp is provided.

A model of the camera is available which will record simultaneously a physical event and an associated oscillograph record.

Warrick Model F Continuously Moving Film Camera (3)

The Warrick High-Speed 35-mm Camera has no shutter and hence is especially useful for streak or oscillograph photography. By utilizing synchronized triggered flash illumination on the subject, it may also be used for motion picture photography. Servo-controlled film speeds from 10 to 125 fps are available (160 to 2000 frames per sec with synchronized flash). The maximum film capacity is 1000 ft. Either a neon NE66 or an argon AR-3 marking lamp is available for time base marking on the film. The unit can be supplied in either 24- to 28-volt d-c, or 110-volt a-c models.

The M. G. D. Company High-Speed Cameras (3)

The M. G. D. High-Speed Camera utilizes movable objectives. It employs a steel drum on the periphery of which 80 identical, equidistant objectives are set. In the interior, this drum has a double row of teeth for driving the film. The normal operating frequency is 3000 frames per sec, and the capacity is 100 ft of 16-mm film. The unit is driven by a 110- or 220-volt universal motor.

The M. G. D. Ultra High-Speed Camera is capable of 100,000 frames per sec. The same optical compensation system is used for the ultra high-speed camera as for the 3000 frames per sec camera. However, 35-mm film, which allows 3 rows of parallel, slightly staggered pictures to be exposed is used. The film itself, about 6 ft long, is applied against the inner surface of the optical drum so that it is driven by the drum in its rotating movement. The exposed film is comprised of 3 rows of pictures, totaling 750.

Winston Electronics Ltd., Image Converter Tube Assemblies (3)

Units with exposure times down to $^1/_{10}$ microsec and frame rates to 2×10^6 per sec are available. A lower rate model covers frame frequencies of 1000 to 20,000, and picture durations, independent of frame rate, from 10 to 100 microsec. Tubes can be furnished to convert infrared or ultraviolet radiation to permit either visible observation or photographic recording of images. Slit scanning models permit streak-type images with a time resolution of the order of 10^{-9} sec.

Examples of Photographic Techniques Applied to Jet Propulsion Studies

Motion picture photography has become a standard tool for obtaining permanent records of certain phases of jet engine firings. Usually the engine is surrounded by a battery of cameras, each covering a definite portion of the system. Thus the performance of each selected part is visually "monitored" during test operation by cameras. Normal speed or high-speed intermittent photography is customarily employed in this application. It is usually desirable in this application to use film capacities greater than 100 ft. Reference (33) discusses some of the photographic problems encountered in rocket firings.

Aside from the strictly monitoring role, the camera has also become a very valuable research tool. It is in this field that high- and very high-speed photography finds its widest application. In order to facilitate its use, it is generally necessary to modify the test engine to make it amenable to photographic techniques. One of the examples of such application is the study of combustion in rocket motors. In order to study photographically the combustion inside a motor, it is necessary to make either the complete motor or part of it transparent. Two distinct methods have been described in the literature and will be reviewed briefly: (*a*) Two-dimensional, transparent chambers, using Plexiglass or Lucite for the flat-sided walls, have been built (34, 35). (*b*) Long observation windows or slits were inserted in the walls of cylindrical chambers (36–38).

A typical "two-dimensional" chamber resembles an axial slice, 0.47 in. thick, cut from a 1000-lb thrust chamber. The over-all length of the chamber from injector face to the nozzle exit is approximately 16 in., and the height in the combustion chamber section is 4.375 in. Plexiglass or Lucite was used for the walls since it was found that the high chamber temperatures melted the surface of the plastic, forming a liquid film. Thus the heat transfer from the hot combustion gases is almost entirely dissipated in melting the surface, and the main body is left intact. The plastic walls are about one inch thick—sufficient for a run of about 5-sec duration. Using high-speed photography, useful knowledge about injector and flame behavior was obtained with these motors. The cameras used for these tests were Eastman Type III, 16-mm motion picture cameras capable of speeds up to 3000 frames per sec. The film acceleration period used up approximately one half of the film. Actual film speeds were obtained by noting the movement of a timing disk shown on each frame or by using timing pips recorded on the film itself. The total time required to expose the available 100 ft of film was approximately 2 $^1/_2$ sec. Kodak Super XX black-and-white and kodachrome color films were used. Of course, the flame emitted sufficient radiation so that no external source of illumination was needed.

A typical slit-type motor consists of a 3-in. diam, 10-in. long cylindrical chamber. The slit is $^1/_4$ in. wide and approximately $8^3/_4$ in. long, extending toward the nozzle from a point even with the injector head face. The principal components of the window assembly are two polished quartz plates, cooled by means of nitrogen gas. Although a 16-mm Fastax movie camera with speeds up to 8000 frames per sec was used in several tests to photograph the radiation emitted from the motor through the slit, the presence of the narrow slit made the use of streak photography a much more useful technique (23, 31, 32). The film of the camera is made to move at a known speed and the shutter is held open during the entire exposure. The camera is arranged so that the direction of motion of the gas along the slit is perpendicular to the camera optic axis and to the direction of film motion. Thus the rocket motor radiation is recorded without interruption. The camera used in these particular experiments was a General Radio Company Type 651, 35-mm continuous strip camera, capable of operating at film speeds from 8 to 80 fps. An externally excited spark gap provided either 60, 120, or 240 cps timing marks on the film edge. Four types of film were used: 100-ft rolls of 35-mm Eastman Kodak Company Super XX, Daylight Type Kodachrome, and Spectroscopic film types 103-O and I-N. As an aid in correlating events with photographs, the following were recorded on a multichannel oscillograph: (*a*) chamber pressure, (*b*) strip camera timing marks, (*c*) voltage pips obtained from energizing various solenoid valves in the reactant lines. By means of this technique it is quite simple to measure the velocity distribution of the radiation emitted along the slit.

Although photographic techniques, unquestionably, are very successful tools in jet propulsion studies, it must not be forgotten that the results obtained require careful and cautious interpretation. The film records only the radiations which emanate from the surface of the flame volume. Hence, it is never quite certain whether the exposed film pictures a local condition at the surface of a cross-sectional slice or an integrated condition across a volume element. Only in combination with other types of instrumentation can the true value of high-speed photography be generally exploited.

Acknowledgment

We want to thank the various manufacturers and distributors of photographic equipment for supplying us with data and information.

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Manuscripts submitted for publication *must* be double-spaced originals. There should be wide margins at both sides of the sheet and triple spacing around formulas to allow for the marking of directions for the printer.

Original drawings (jet black India ink on white paper or tracing cloth) should accompany the manuscript. (*Blueprints are not acceptable.*) Photographs must be on glossy white paper. The *smallest* lettering on 8- by 10-in. figures should be no less than $^1/_4$ in. high.

Only the simplest formulas should be typewritten, all others should be carefully written in pen and ink. The difference between capital and lower-case letters and Greek symbols should be clearly distinguished.

SEE PAGE 114 OF THIS ISSUE FOR FURTHER DETAILS

Sampling and Analysis of Combustion Gases

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Cornell Aeronautical Laboratory, Inc., Buffalo, N. Y.

Rapid cooling of combustion gas samples in order to "freeze" the high temperature composition is discussed. Small diameter sampling probes have used expansion, dilution by inert gas, and cooling from the tube wall, and have accomplished significant cooling in a few microseconds. Based on some experimental tests, this cooling time is judged to be satisfactorily short. Analytical methods for combustion gases are discussed with emphasis on those newer methods of significant promise, mass spectroscopy, infrared and ultraviolet absorption spectroscopy. The latter are especially noted, since they are applicable while the gases reside in the reaction chamber. Mass spectroscopy and Orsat analysis have yielded similar results on given samples.

A KNOWLEDGE of energy release and of the thrust developed in a rocket motor is of prime interest in an understanding of its operations. These are dependent upon the chemical reactions taking place within the motor and upon the products of the reactions discharged through the nozzle. The high temperature at which the reactions occur interposes a difficulty in the direct study of the reactions and compositions. During residence and discharge, the gases exist in states which are not stable at low temperature. Carbon dioxide is a notable example. At high temperature it is dissociated to carbon monoxide and oxygen. When cooled slowly, these reassociate to carbon dioxide, releasing heat and changing the average molecular weight of the discharged gases. Water is similar except that its dissociation occurs at somewhat higher temperatures and more energy is involved. If a sample of gas is withdrawn from the hot combustion zone and then analyzed at low temperature, reassociation reactions may occur within the sample during its cooling, so that the composition of the gas when analyzed may differ markedly from its composition when in the hot combustion zone. In addition to the dissociation products of carbon dioxide and water, there may be many other intermediate products of the combustion reactions, such as fragments of hydrocarbon molecules, ions, etc., which exist briefly in various regions of the combustion zones but which disappear even before the gases leave the nozzle and which would normally disappear from a sample when cooled, although a special method for detecting them is mentioned later. Carbon dioxide and water are of especial importance, however, because one or both are present in the products from most fuel combinations and they are always discharged from the nozzle in a partially decomposed state, since this results merely from the high temperatures involved. In contrast, sufficient combustion chamber volume may prevent the discharge of intermediate products, thereby preventing the attendant energy loss. Were combustion temperatures sufficiently high, decomposition of O_2 and N_2, and discharge of their atoms would represent a similar energy loss.

The above considerations point to the desirability of making an analysis of the hot gases without cooling or removing them from the reaction zone. In principle this is at least partially possible by physical means, e.g., absorption spectroscopy. Such means are desirable if the intermediate products of combustion are to be studied, although the chemical detection of free radicals is being investigated. For study of such materials as H_2, CO, and O_2 (and also of O and N, should temperatures be high enough to make their presence significant), sampling and analysis at low temperature are possible if the sample can be brought to low temperature with sufficient speed. This is feasible because their recombination proceeds very slowly at low temperature, which is illustrated by the fact that a mixture of hydrogen and oxygen at room temperature undergoes no reaction for indefinite periods if nothing, such as a spark or catalyst, is present to initiate the reaction. Thus an instantaneous cooling would "freeze" the gases at a composition they had at high temperature.

Gas sampling and analysis have, of course, been widely used in many applications. When dealing with hot gas, cooling has often been resorted to as a means for prolonging the life of the sampling probe. The discussion here, however, is limited to a few illustrative cases in which rapid cooling was studied or attempted in order to freeze the high temperature

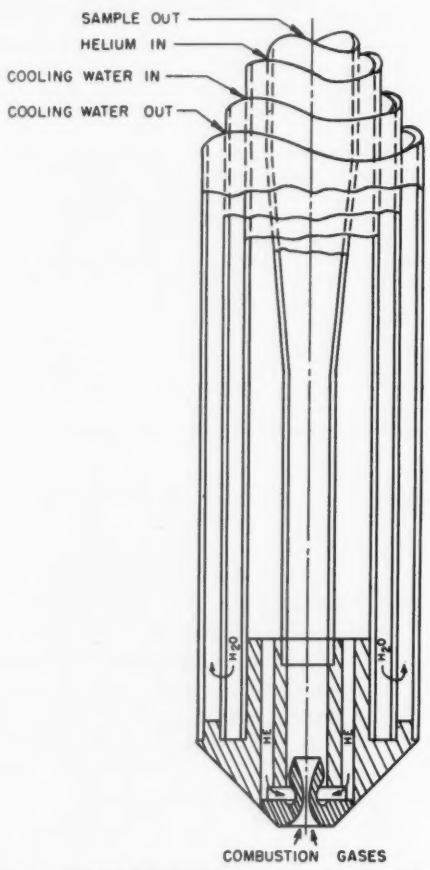

FIG. 1 EXPANSION AND DILUTION TYPE SAMPLING PROBE

(From Ref. 4)

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composition, and to recent analytical techniques used in combustion research. For broader discussions of gas sampling and analysis, review articles, such as those by Darby (1),[3] et al., and Nash (2), are available.

Three general methods are available for accomplishing the sudden cooling of a gas sample. Its heat may be extracted from the gas as a whole, as by transferring the heat to the cooled wall of a sampling tube through which the gas passes. The thermal energy of the molecules may be dissipated by an expansion, such as that involved in conversion to translational energy by isentropic expansion in a nozzle. Further, the hot molecules may be cooled by dilution with a cold unreactive gas so that the collisions between gas molecules during the process produce no reassociation reactions. In all processes, some small time delays are involved.

It may be well to distinguish one type of delay which is inherent and is known as relaxation time. It is a time involved in the transformations of thermal energy associated with vibrational and rotational degrees of freedom within the molecule. During this time, the energies contained in the various degrees of freedom pertaining to a single molecule have not attained equilibrium. For many gases, the relaxation time is small. Measurements by Kantrowitz (3) show it to be 1.18×10^{-8} sec at 207° K for hydrogen, which here seems negligible, and similarly small for some other gases. Further, the relaxation time decreases with increasing temperature. The value may be much larger for some gases. Nitrogen, for example, has a relaxation time of 2.6×10^{-3} sec at 761° K. It appears, however, that even long relaxation times should be unimportant because, if other phases of the cooling are more rapid than the relaxation, no reassociation reactions should occur, inasmuch as the number of collisions per second and the collision energies will be small during the relaxation time.

An excellent example of sudden cooling by rapid expansion together with dilution by a cold inert gas has been provided by work carried on at the Jet Propulsion Laboratory (4). The sample was drawn into a sampling probe through a converging-diverging nozzle of small diameter and expanded to a low pressure. Cooled helium was drawn through a surrounding nozzle, in annular form, and mixed with the sample at the low pressure. This probe is illustrated in Fig. 1. The throat diameter of the sampling nozzle used was 0.0093 in., and the rate of flow was approximately 10^{-5} lb/sec. The time required to reduce the temperature from that of the natural gas-air flame sampled to 1500°F is stated to be approximately 10^{-5} sec. Tests of the probe were made, using pressures within the probe ranging from 1.8 to 18.2 mm Hg. The data indicate that the percentages of CO, CO_2, H_2, O_2, and H_2O obtained in the analysis of the resultant sample varied with the pressure, and further study using higher pressures was recommended. Analyses were made by Orsat, after recompression, and by mass spectrometer, and good agreement between these methods was noted.

The rate of cooling of a gas sample withdrawn through a cooled tube of small diameter, without dilution or appreciable expansion, may be computed. In work at Cornell Aeronautical Laboratory (5), a common equation expressing the rate of heat transfer from flowing gas to a tube wall was used to obtain[4]

$$\Theta = \left(\frac{1}{1.75\pi}\right)^{3/2}\left(\frac{\pi D^2}{4}\right)\left(\frac{Pr}{\nu}\right)\left(\frac{T_1 - T_2}{\frac{T_1 + T_2}{2} - T_w}\right)^{3/2} \quad \ldots [1]$$

and

$$L = \frac{4w\Theta}{\pi D^2 \rho} \quad \ldots [2]$$

in which Θ is the time for the gas to cool from T_1 to T_2 while traveling the distance L in a tube of diameter D whose wall is maintained at T_w; w is the weight flow rate; and Pr, ρ, and ν are Prandtl number, specific weight, and kinematic viscosity, respectively. It is interesting to note that Equation [1] indicates that the cooling time is independent of the sampling rate.

A water-cooled sampling probe was constructed using a stainless steel tube approximately 0.02-in. inner diameter. This is illustrated in Fig. 2. Applying the equations to it for the case in which Pr/ν is similar to that for air at atmospheric pressure, computed cooling times and lengths are as shown in Table 1. The values pertain to a gas initially at 4480° R, sampled at a rate of 0.476×10^{-5} lb/sec (100 cc/min) with the tube wall at 560° R.

TABLE 1 COMPUTED COOLING IN SAMPLING PROBE

Gas temperature, T_2, ° R	Cooling time, sec	Length, in.
4480	0×10^{-6}	0×10^{-3}
3920	1.29	4
3360	4.5	12
2800	10.5	25
2240	21.6	48
1680	40.6	83
1120	74.0	137

Unfortunately, data on speeds of the reassociation reactions at high temperature were not well enough known to judge, from a theoretical basis, the possible efficiency of the cooling

[3] Numbers in parentheses refer to the References on page 177.

[4] The equations are here given in a form modified from that of the reference.

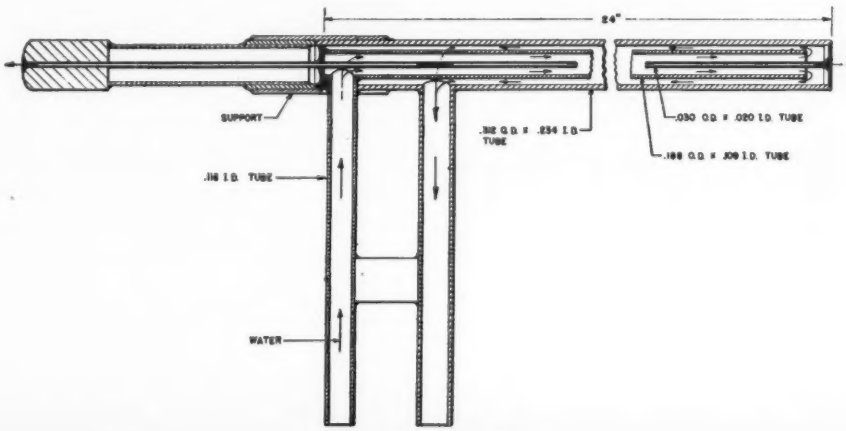

FIG. 2 COOLED SAMPLING PROBE

in this probe. Its action was investigated experimentally by two means. In one, gases were sampled from the hottest region of an open flame of natural gas and oxygen, and the samples were analyzed by Orsat apparatus. It was found that $(CO_2)/(CO)(O_2)^{1/2} = 11.98$, which corresponds to equilibrium at 4660° R, and $(H_2O)/(H_2)(O_2)^{1/2} = 67.2$, which corresponds to equilibrium at 4760° R. The close agreement of these computed temperatures indicated that both reactions were frozen in the same temperature. This is most easily interpreted to mean that this temperature was the local one of the gases sampled and that the high temperature composition was successfully frozen. More positive results were obtained for carbon dioxide alone at a lower temperature. Purified gas was held at high temperature in a Sillimanite tube enclosed in a hollow Globar element. Two samples, each of two liters, were withdrawn through the cooled sampling probe, and the sample analyzed for CO_2, CO, and O_2. One corresponded to equilibrium at 3510° R as compared with an experimentally measured temperature of 3540° R; the other corresponded to equilibrium at 3490° R as compared with the experimentally measured temperature of 3500° R. This agreement is within the accuracy of the temperature measurements. Similar tests with water dissociation were not attempted because of the difficulty of finding materials capable of withstanding temperatures at which dissociation would be appreciable.

In addition to the cooling problems noted above, obtaining a representative sample for analysis may offer difficulty. If the sampling tube withdraws gas from the combustion zone at a slow rate, there may be a relatively stagnant zone created in the region of the entrance. Composition at this point may then differ from that otherwise occurring at the same point because of different rates of diffusion of components or different times for reaction. In work at Princeton University (6), this problem was solved by control of the sampling rate using a pneumatic Venturi which introduced the gas into the sampling system at the same velocity as that of the gas passing the point of entry of the probe. The gas then flowed through a gas sampling bottle, and after sufficient time to flush the partially evacuated bottle clean of previous gas, an amount of gas was suddenly trapped in the bottle for use as a sample. Samples were taken at 10-sec intervals using sampling bottles in parallel. Simultaneous samples were taken from various probes and the complete system was electrically operated.

The composition of gaseous combustion products (unburned fuel, CO, CO_2, H_2, O_2, H_2O, N_2, intermediates, etc.) of jet propulsion devices has been sought by applying most of the known analytical techniques and methods, from the conventional, time-honored Orsat method to the latest developments in the field of absorption spectroscopy. Improvements in the Orsat method and the other chemical methods of analysis and the development of spectrographic methods have been adequately treated in the afore-mentioned review articles (1, 2).

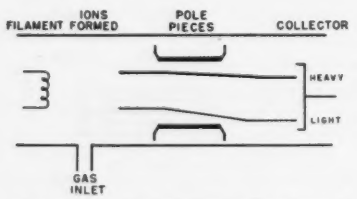

FIG. 3A SCHEMATIC OF MAGNETIC DEFLECTION TYPE MASS SPECTROMETER

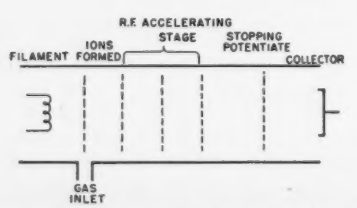

FIG. 3B. SCHEMATIC OF R. F. TYPE MASS SPECTROGRAPH

Among the special applications, the mass spectrometer has retained the interest of researchers in the combustion field because of its inherent potentialities of diversity and accuracy, in spite of the physical difficulties encountered in applying the method in the combustion laboratory. A chief difficulty has been encountered in transferring a stabilized representative sample from the hot combustion chamber to the rarified atmosphere of the mass spectrometer. In recent work by the Jet Propulsion Laboratory (7), a gas sampling stream was continuously withdrawn through the double orifices of a pneumatic temperature sampling probe into a long tube in which any pressure fluctuations arising in the motor were well dampened. A fraction of this gas was continuously bled off through a capillary orifice into an expansion chamber, monitored at 10^{-2} mm of Hg by a thermocouple-type vacuum gage. A second narrow capillary connected the sample chamber with the mascope[5] tube and provided an additional pressure drop so that the mascope was maintained at 10^{-4} mm of Hg. It is interesting to note that these workers have adapted the radio-frequency mass spectroscope originally designed by Bennett (8), in place of the conventional magnetic deflection type.[6] Since the ion currents that can be developed in the Bennett tube are several orders of magnitude larger than those attainable in the conventional magnetic mass spectrometer, the radio-frequency mascope lends itself to rapid continuous analysis of a flowing gas which may be changing in composition. The only analytical data presented in (7) are for air samples, from which it was concluded that the apparatus and techniques should yield satisfactory results for combustion gases. The theory and design of the radio-frequency mass spectrometer are fully discussed in both (7) and (8).

A technique for continuous analysis of a three-component gas mixture with a mass spectrometer has been developed by Hunter, et al. (9). Since this was a conventional magnetic deflection instrument, high accuracy of analysis was sacrificed in favor of a high response speed.

Investigators at the NACA Lewis Flight Propulsion Laboratory, Cleveland, Ohio, and at the Johns Hopkins Applied Physics Laboratory, Silver Spring, Md., have employed mass spectrometers in combustion research, but no published results were uncovered in the unclassified literature to date.

Infrared spectroscopy has been developed to a high degree of refinement as an analytical tool, especially in the petroleum industry. However, since this method cannot be used for monatomic and symmetrical diatomic molecules, it has not been as useful in combustion work as a tool for chemical analysis as it has for temperature determinations. Commercial instruments require a considerable path length of sample and are relatively slow. Fowler has overcome these deficiencies in an infared gas analyzer, designed primarily for physiological research (10). However, this system, which gives a 90 per cent electrical response in about 0.1 sec with samples as small as 0.5 cc in an optical path of 0.4 cm, warrants consideration as a tool for analyzing combustion gas samples, particularly since it also provides for continuous sampling.

Other continuous-flow infared analyzers have been used to

[5] Mascope—a contraction used throughout Ref. (7).

[6] The difference in operating principle between the two types is illustrated in Figs. 3a and 3b. In the conventional magnetic deflection mass spectrometer, gas molecules are ionized, focused, and accelerated in a beam, and sorted by passing through a magnetic field which deflects the ions in proportion to their mass so that each species can be collected separately. In the radio-frequency mass spectrometer, the gas molecules are ionized, accelerated by a phased electrical potential, and are sorted by encountering a potential of opposite sign and such magnitude that only certain ions with kinetic energy values in excess of a prescribed value penetrate to the collector.

determine continuously the concentration of carbon monoxide and carbon dioxide in flue gases (11); the determination of methane in a stream containing other hydrocarbon gases, and also the fraction of ethylene oxide in catalytic oxidation of ethylene gas (12). Numerous other applications of this method to pilot plant operation are cited in the literature. As one specific illustration of automatically operated apparatus, the description by workers at the Gulf Research and Development Company (13) is mentioned.

Glasser has discussed the ultraviolet method of continuous gas analysis (14). Generally, the substituents of interest in combustion reaction involving conventional fuels and oxidizers do not absorb in the ultraviolet and, hence, are not subject to determination by this method. Certain emitters in hydrocarbon flames, such as H-C and C_2, emit strongly in the ultraviolet, and Bauer (15) has suggested that ultraviolet absorption techniques might be used to determine their concentration.

An effort to adapt the Mach-Zehnder optical interferometer to the measurement of chemical composition and temperature of gas mixtures has been reported by Olsen (16). The method has been applied successfully to a two-dimensional, two-component gas jet. For the three-dimensional case, a space-time average composition and temperature will be obtained across the path traversed by the line-of-sight of the instrument. The technique was developed to study steady-state combustion in Bunsen flames. Its application in combustion research has been limited by the complex composition of the combustion gases, the steep temperature gradients in the flame, and a lack of suitable data on the refractive index of the gases at high temperature.

Gases differing in the thermal conductivity may be analyzed by a procedure which determines the rate of thermal conduction through a sample in comparison with a standard (2). In this method, two thermal conductivity cells which consist of equal platinum resistance wires located concentric to and insulated from outer tubes are connected as two arms of a Wheatstone bridge. When the wires are heated they lose heat proportional to the thermal conductivity of the gases in the cells. The unbalance in the bridge caused by the difference in wire resistances (i.e., heat losses) is related to the analysis by previous calibration. Generally the greatest accuracy can be obtained in a mixture of gases in which the gas to be determined differs considerably from the others.

An interesting chemical method for determining reaction intermediates in combustion reactions has been advanced by Bennington (17). He has demonstrated that the free radicals, methyl and atomic hydrogen, may be captured by an organic free-radical triphenyl methyl. Only preliminary results are reported, but research efforts on the method have been continued.

In summation, it is noted that while sampling and analysis of combustion gas in rocket research are far from stabilized or free from problems, many promising methods are available. Selection of the most appropriate ones depends upon the particular system to be studied and the information sought. Scrutiny of any particular method used and of the accuracy of the results is generally necessary.

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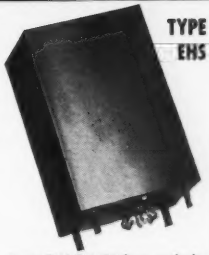

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Flow Controls

KURT R. STEHLING[1] and PHILIP M. DIAMOND[2]

The construction and operation of various types of flow controls are outlined. The largest group of controls—valves—is discussed in detail. While commercially available valves can often be used for rocket power plant practice, in some instances where space and weight are at a premium, "custom made" controls must be used. The role of the accumulator, as a non-valve type of control, is outlined and its function as an energy-storing device and fluid oscillation damper is emphasized. The operations of other important flow control devices, such as cavitating Venturis, calming chambers, flow pulsing units, etc., are described. A typical rocket firing stand is described, and the functions of various flow control units are reviewed.

Introduction

A LIQUID propellant rocket engine is inevitably part of a complex hydraulic network whose function is the transportation and control of the flow of a fluid or fluids.

The flow control function is most important since the rocket engine is peculiarly sensitive to the proper and closely timed sequence of propellant flow initiation, shutoff, and throttling. This function is normally obtained with various types of valves and other rocket motor accessories. The design problem of these units is complicated by the nature of rocket propellants which are usually either extremely cold (liquid oxygen), corrosive (nitric acid), or detonable (nitromethane).

Valves and variations of valves form the largest group of flow control devices; however, such other important accessories as accumulators, orifices, Venturis, and liquid level controllers serve a more limited but nevertheless important function in regulating propellant flow.

In some phases of rocket motor research and development, controls are required which have unique and specific properties. Some of their functions are the creation of oscillating or pulsating fluid flow, or conversely, the smoothing of a fluid flow. Examples of the former are oscillating flow valves or fluid pressure pulse units; and of the latter, cavitating Venturis, calming "chambers," and accumulators.

Since valves are the largest group of flow control devices, some of the more prominent and common types will be discussed at some length. Applications and details of other flow control devices will also be outlined. A description, diagram, and photograph of a representative static rocket-motor test pit, flow control system are included.

Valves

No complete attempt can be made here to outline the operation and construction of the multitude of valves currently available for rocket and jet-propulsion test operations. This applies to both commercially available units and those designed for a particular application. Various designers often find it necessary and expedient to design their own valves and flow control units, since commercial units have sometimes not been found acceptable or available for the rigorous service conditions encountered in the field. Since much of this information is proprietary, it is possible to discuss such valves only cursorily.

A common and versatile valve is the "poppet valve" (Fig. 1) which, in principle, is as old as the art of construction of fluid systems. It consists, essentially, of a valve seat and a poppet which is designed to positively stop or regulate flow. Since all of the components of this type may be on the same axis, a rugged and dependable valve may be made despite the necessity of maintaining close tolerances. Due to the corrosive action of many of the fluids used, valve seats and seals as well as the lubricants used must be chemically stable and preferably inert. The new halogenated plastics, oils, and greases are ideal; the silicone rubbers, oils, and greases are especially adaptable for low-temperature service. Plastics used for seat materials, such as Teflon and Kel-F, have a basic disadvantage; these materials flow under the high unit loadings experienced. The part in which the plastic is mounted must be so designed that the plastic is as completely enclosed and supported as possible.

The poppet may be designed with or without a pintle. The purpose of a pintle is to regulate and control the transient stage of flow through the valve from the point of zero flow to full flow. It is desirable in most cases, and necessary in some, to precisely control the initiation of flow. A sudden pulse of full flow may actually do structural damage, while, for instance, an improperly regulated initial flow to a rocket motor may lead to faulty starting and aggravated combustion stability effects. Thus, a pintle may be designed on the basis of conventional hydraulic theory, practice, and experiment as well as on actual rocket motor experience. The shape of the pintle is, of course, determined by the desired flow rate characteristic and may be conical, paraboloidal, ellipsoidal, or any other shape which is warranted by the flow case.

Attached to the poppet is a stem which is then connected to some type of actuator. Most commonly, actuation is ob-

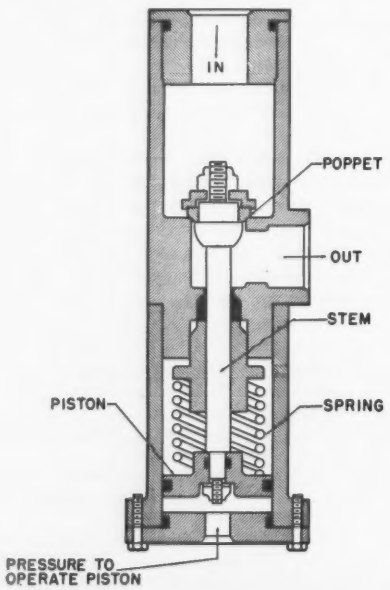

FIG. 1 POPPET VALVE, NORMALLY CLOSED

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tained with hydraulic or pneumatic pistons and cylinders. The method is the most desirable because of the usual availability of pressurizing gas and because of the small size of actuator components. In very small valves it may be more expedient to use electrical actuation. Solenoid and motor-driven actuators are widely used in both missile and test stand service.

The basic poppet design may be adapted to many purposes. It is used for open-and-shut valves, metering valves, check valves, vent valves, regulating valves, etc. (*A*).[3] Multiple units may be used in parallel beam-linked assemblages or connected on the same axis.

In particular, multiple assemblages are often used for "propellant valves" for control of rocket motors or gas generators. These types of valves are compact and efficient and are especially suitable for controlling and sequencing the flow of more than one liquid. They are usually fluid operated using a piston and cylinder. On test stands it is usual to have more than one set of propellant valves for reasons of safety and flexibility. Unless an actual missile configuration is tested, it is common to have a set of two independent single fluid propellant valves mounted on the test stand and a set mounted near the propellant tanks. Hence, these are called fuel and oxidizer stand and tank valves. Propellant valves are generally gas operated and spring loaded for the return stroke.

For ideal operation, propellant valves should open and close quickly, and have no chatter or water hammer effects associated with the operation. Quick response is obtained with a valve when the following conditions are adhered to: (a) High pressure actuating source; (b) sufficient piston area; (c) minimum opposing areas; (d) low friction; (e) low actuating

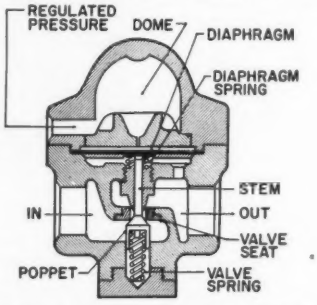


FIG. 2 GROVE REGULATOR COMPANY DOME REGULATOR VALVE

fluid viscosity; (f) large actuating fluid ports; (g) high return spring force. In valves of this type, chattering becomes a problem when the forces resulting from the operation of the valve are nearly balanced when the valve just seats. Then, any small force fluctuation, most often caused by the flowing fluid, opens the valve; the restoring force then closes it and the cycle repeats. When the fluid is flowing in a direction which tends to close the valve, the same cycle of events could occur. This is obviously an undesirable effect and may be eliminated by designing the valve to open and close positively.

However, the precautions taken to assure positive and fast action may result in the valve poppet suddenly and swiftly accelerating to a closed position. This could result in a series of pressure waves which alternate from positive to negative levels and may be accompanied by dangerously high pressure surges. This is called "water hammer" and may be prevented by designing the valve to close relatively slowly; alternatively, its effects could be diminished by the use of relief valves which permit some liquid to escape when the pressure exceeds a certain value. Also, gas-filled accumulators (described later) of suitable sizes will tend to absorb some of the shock.

All types of valves may be used in various configurations and combinations to form units of fluid system controls such as regulator valves (*B*). The fluid balance type of regulator (Fig. 2) is used to meter a large flow of gas which must be maintained at a constant pressure level. A poppet stem is fastened to a diaphragm which is under constant pressure on one side; and the pressure to be regulated is applied to the other side. When an unbalance exists, the diaphragm tends to open or close the valve so as to maintain the properly regulated pressure.

Another type of regulator (Fig. 3) based on the action of a spring to maintain a constant force of a diaphragm is used for low flows. The valve opens to admit high pressure gas until the spring force is balanced. When the spring force is

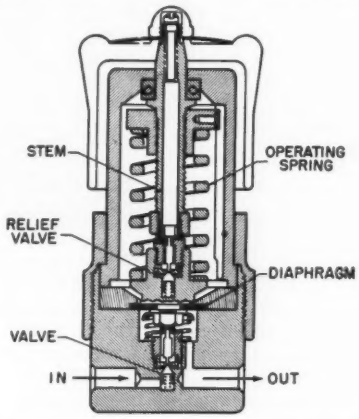


FIG. 3 GROVE REGULATOR COMPANY HAND LOADER

smaller than the pressure force the valve opens to permit this pressure to bleed off to the atmosphere. This spring loaded regulator valve can be readily adjusted for a wide range of pressures by varying the spring force. Because of this factor these valves are convenient for use on test panels and in rocket test cells.

Regulator valves, when set to operate at specific pressure levels, must be used with a source pressure which is maintained at a much higher level than the regulated pressure. As the decreasing source pressure approaches the regulator pressure, the regulator goes "off control" and becomes useless. The rising or falling characteristics of a regulator valve may also be influenced by the operating temperature. The great difference from design conditions of density and other physical properties often gives rise to differences of several per cent from design pressure. The object, with respect to temperature, is to minimize the problem and make the performance change negligible.

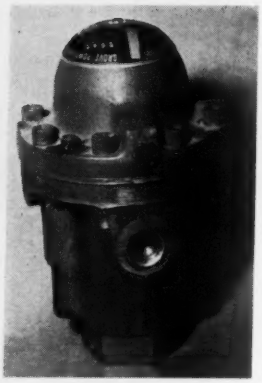
In many cases the two types of regulators are combined to form a regulation "system." In general, the spring loaded bleed regulator is a low flow device, while the fluid balance regulator may be designed for high capacity. It is natural, then, to employ the former as the constant pressure source for the latter which in turn regulates the large flow of fluid.

Typical of this system is the combination of Grove Loader and Grove Regulator shown in Figs. 4 and 5. The hand-operated loader pressurizes the dome of the regulator to any desired setting from 0 psi to the operating limit. The loader may be installed remotely from the regulator; as, for example, on a test engineer's panel in a control room of a rocket motor test cell, where the regulator may be in the cell proper. Of course, where only low flows are necessary, the loader may be used by itself.

For missile use, it is sometimes required that a large flow of

[3] Italic capital letters in parentheses refer to the Representative Commercial Sources listed at end of the paper. The manufacturers listed are representative producers and are not necessarily the only or best available. A more complete listing may be found in various technical and trade journals (e.g., *Aero Digest*, vol. 66, March 1953, p. 98) and in the advertisements that appear from time to time in this JOURNAL.

(*Left*)
FIG. 4 GROVE REGULATOR COMPANY HAND LOADER



(*Right*)
FIG. 5 GROVE REGULATOR COMPANY DOME REGULATOR VALVE

gas be regulated; for instance, in the use of pressurized propellant tanks. Here the tank pressure must be so regulated that the final propellant flow is correct. It is general practice to assemble a set of regulator valves similar to those described above in a unit, together with the necessary check valves, pilot valves, vent valves, etc. This assembly is commonly termed a regulator valve package and is the key unit in the gas system of a missile.

Two hand-operated valves for use where accurate metering is less important are the gate valve and the globe valve (*C*). The gate valve consists of a sliding "gate" fastened to a hand wheel which raises or lowers the gate. When opened, it is possible to see directly through the gate valve passage. It is designed to have a low pressure drop when fully opened and is not particularly sensitive with respect to control. These valves are used primarily where it is only necessary to either completely close or completely open the valve. Their construction is such that repeatable and predictable flow control is difficult. This type of valve must be carefully adjusted, since the degree of opening is not linear with turns of the hand wheel. This is due to backlash in the screw thread and large clearances resulting from the deliberate nonprecision design.

The globe valve, sometimes called a needle valve, works on the poppet principle except that the poppet is merely a rod with a tapered end which fits into a seat. The rod is fastened to a hand wheel threaded to the body of the valve. In operation, the hand wheel is turned, screwing the tapered stem toward or away from the seat. The stem is tapered for two reasons: The first is that an angular contact results in a better valve seal. Secondly, the tapered portion provides finer control of the flow area because the area increases approximately with the sine and tangent of $^1/_2$ of the cone angle of taper. For control of flow of gases, this type of valve is excellent. It is used to adjust flow on test panels and fluid lines where it is only necessary to vary the flow qualitatively, as compared to regulators which vary flow quantitatively.

In any system it is most expedient to have an initial control of the system through an electrical method. Solenoid actuated valves (*D*) are suggested at once and, in fact, are widely used. For high pressure systems, large solenoid valves are not practical because of the large sizes of solenoid and the great amount of power required. Therefore, small pilot solenoid valves are used to provide a source of actuation for larger units and thence to operation of the entire system. These solenoid valves are, for instance, used to actuate propellant valves. The solenoid valve is inserted in the actuating gas line, between the actuating cylinder of the propellant valve and the gas source. When the solenoid valve is energized the propellant valve is actuated. When the solenoid valve is de-energized, the actuating pressure is vented and the propellant valve closes. Commercial solenoid valves are guaranteed for response times on the order of 50 millisec and often actuate in 30 to 40 millisec, with a low limit near 18 or 20 millisec.

A typical 3-way solenoid valve is shown in Figs. 6 and 7. It is termed 3-way since it has three different ports which serve the functions of an "in" port, an "out" port, and a "vent" port. The source pressure enters at port A and is stopped at valve seat 1. When the solenoid is energized, the poppet which has closed off seat 1 is lifted off the seat. Immediately, however, the lower spring pushes the lower poppet to close off flow at seat 2. Now the flow has been stopped at

FIG. 6
GENERAL CONTROLS, INC., 3-WAY SOLENOID VALVE, GAS SERVICE, 1500 PSI

seat 2 and can only proceed out of the valve at port B. When the solenoid is de-energized, the upper poppet is pushed back to seat 1 by the upper spring and the lower poppet is pushed off seat 2 by the guide pin. This stops the flow of source pressure and allows pressure at port B to vent off to atmosphere through port C. This type of 3-way, as well as 2-way and 4-way valves find use in rocket test cells actuating propellant valves, on test panels in laboratories, for convenient shutoff valves in testing equipment, and in missiles for operating other components.

An extremely important component in any fluid system is the check valve. This valve permits flow in one direction and stops flow in the other. Check valves are usually lightly spring loaded so that they are positively acting and are not totally dependent on back flow for their actuation. They are used to prevent corrosive fluids from backing up in lines, to hold pressures downstream of a point, etc.

Check valves are generally of the poppet type and sometimes chatter or vibrate when the flow through them becomes small and the downstream pressure closely approaches the upstream pressure. This may occur when a check valve is inserted in a gas line immediately before a tank which is to be pressure-regulated through the check valve. When the tank pressure decreases slowly, the check valve may tend to chatter.

An unusual type of valve is the frangible disk (*E*), which when used once, must be replaced. It consists of a disk of metal of proper size placed in a fluid line such as a tank vent. When the pressure on one side rises to a critical value, the disk breaks and the fluid flows through the valve. In a pressurized tank vent line it functions as a pressure relief valve. In

this instance, it acts as a burst disk or a rupture diaphragm. The frangible disk may also be used in propellant lines to separate two liquids which must be flowed through the same line. When pressure is applied to the system, the disk breaks and the fluid flows.

There are two basic types of frangible disks: flat, and contoured. The flat disks may be made in two pieces, one of which has a U-shaped cutout in it. The disk will break along this cutout and form a smooth flow passage. Thus, this type is used in fluid lines as mentioned previously. The contoured type is often manufactured in a spherical shape and breaks to form a rough, jagged, "flower petal" pattern and is used as the safety valve. The spherical type lends itself to more rigorous design calculations under spherical pressure vessel theory, but both types must still be designed on the basis of experiment. In commercial practice the spherical disks are accurate to 6 to 10 per cent of their rated value, while others are less precise. Variables affecting the burst pressure include material, thickness, and shape of the disk, as well as the contour of the mounting surfaces. The disks are manufactured in batches and a representative fraction of each batch is tested to determine the actual burst pressure. When a disk breaks, there is an impulsive load equal to the area of flow times the burst pressure. In many cases this is a considerable force and provision must be made in the system to absorb this load. A convenient device for this purpose is a two-way or four-way lateral vent cap which directs the escaping gas in opposed jets so as to neutralize their thrust.

Due to the explosive nature of many of the rocket propellants used, it is often desirable to limit the quantity of propellants which accumulate in the thrust chamber after shutdown. The mass of propellants which are in the lines downstream of the propellant valve may be sufficient to cause an explosion; however, if the flow of one of the propellants is stopped close to the chamber the probability of explosion is decreased. A valve built into the injector head, controlling one of the propellants, may be used for this purpose. The valve may be spring loaded and actuated automatically by the propellant flow which initially is controlled by the propellant valve.

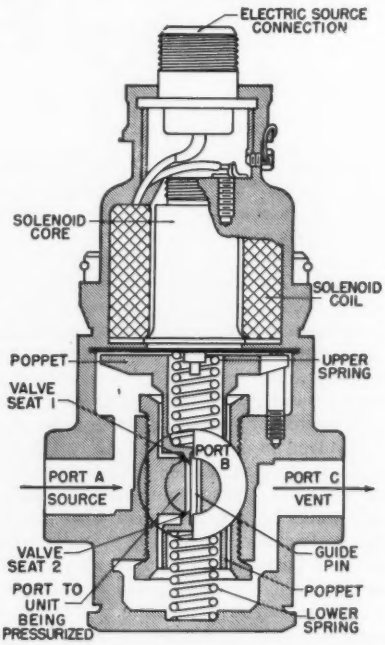


FIG. 7 GENERAL CONTROLS, INC., 3-WAY SOLENOID VALVE, GAS SERVICE, 1500 PSI

Non-Valve Type of Controls

A non-valve type of control device (Fig. 8) is an accumulator (*F*). An accumulator consists simply of a chamber, often spherical, and a flexible diaphragm which divides the chamber volume into two parts. Ports are provided to each of the two sections. The accumulator may be used as a pressure transmitter, permitting a gas to pressurize a liquid without physical contact. It is used as a device to store energy in the form of high pressures, to be released when desired. Many high-pressure test stand sources are energized in this manner. A small capacity pump raises the accumulator pressure to a high valve over a relatively long period of time. This pump is generally a hydraulic fluid pump, and the accumulator transmits this liquid pressure through the diaphragm to a gas, which is released at the operator's convenience. With one end sealed and the other end connected to a fluid line, an accumulator will damp out oscillations by storing energy during a positive part of the cycle and releasing it during a negative part of the cycle. Ordinarily, accumulators use a rubber, synthetic rubber, or other plastic diaphragm. For special service, other materials, which may not be as flexible as rubber, must be used. For extremely corrosive fluids, such as acid, teflon bellows may be used instead of a diaphragm. Metal bellows also may be used. The principal uses are as a transmitter and as an energy storage device. Considering the propellant valve as an example, the accumulator used as a pressure transmitter is placed between the actuating gas source and solenoid valve or other initial actuating device, and the propellant valve. Hydraulic fluid or other liquid may be used between the accumulator and propellant valve actuating cylinder. Using a liquid, such as hydraulic fluid, permits convenient adjustment of the rate of motion of the piston, by the simple expedient of putting an orifice in the line.

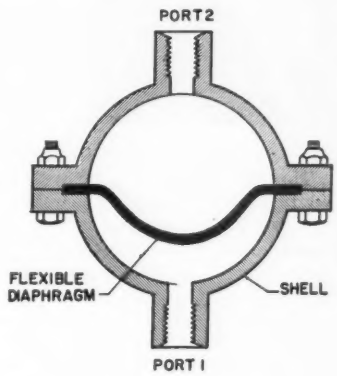


FIG. 8 ACCUMULATOR

Another flow control device, which is a composite unit, and similar in purpose to the cavitating Venturi is considered in this category. This unit is called, simply, a flow control valve, and is composed of an arrangement of pistons, orifices, valve assemblies, springs, and adjustment devices. These valves are used to meter flow under two conditions: constant flow with varying pressure, and constant pressure with varying flow. In addition to their prime purpose, these valves may be equipped with check valves, relief valves, etc., to suit particular applications and conditions.

The Vickers Flow Control Valve is typical of a constant flow valve. It operates on the principle of a hydraulic feedback or servo unit wherein the pressure drop across a variable area orifice is used to balance a piston-operated valve. The variable orifice is used, in this case, as the adjusting mechanism.

This type of valve may be used to regulate the flow of propellants to a rocket motor. With further development, this flow control unit could be designed for application with

variable thrust motors. When a single thrust chamber is used for variable thrust, it is usually desirable to vary propellant flow while holding the fluid pressure constant. At present, variable thrust units utilize complex plumbing and valving controls or consist of several thrust chambers which

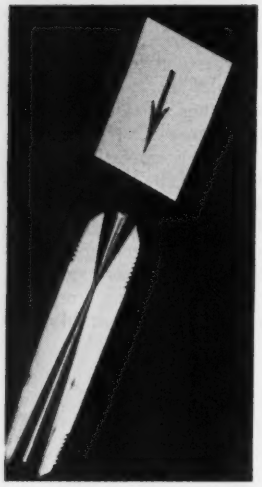


FIG. 9 CAVITATING VENTURI HALF SECTION, 0.060 THROAT DIAM, $^1/_2$ IN. TUBE SIZE (ARROW SHOWS DIRECTION OF FLOW)

are operated singly or in groups to develop the required thrust.

Three important flow control devices are the cavitating Venturi (Fig. 9), calming chambers, and flow pulsing units. The first two are passive devices, since their configuration is independent of the flow condition, while the third is a dynamic part. Cavitating Venturis (1)[4] are used where an essentially constant pressure source of flow exists and where a downstream pressure disturbance may affect the flow. The cavitating Venturi is normally placed between the source and the disturbance. The property which makes the Venturi useful is that (assuming "proper" design) the flow through the throat of the Venturi depends only on the source pressure and not on the downstream characteristics, up to a particular downstream pressure. The downstream pressure point at which the Venturi goes "off control" is generally about 70–80 per cent of upstream pressure and may be as high as 90–93 per cent depending on the surface finish of the Venturi, etc. The proper design criterion is that the fluid pressure at the throat be the vapor pressure of the liquid flowing. If the throat pressure is the vapor pressure, then all static head has been converted to velocity head except for the vapor pressure. If, as has been stated, the upstream pressure is held constant, then it is impossible to affect the flow by changing the downstream pressure. In general, these Venturis must be designed to suit a particular installation due to the peculiar nature of rocket motor requirements. Another possible application is that of propellant injection into a thrust chamber. It could result in a method of injecting the propellant in a semigaseous state. Since all of the liquid tends to vaporize at the throat and a short distance beyond, it could be possible to cut the Venturi off near the throat and inject partially vaporized propellant directly into the chamber.

A calming chamber is a device whose primary function is to free a flow of gas or liquid from vortices, eddies, and other turbulent flow conditions. Secondary, the chamber may change the rate of flow, dynamic and static pressure or direction of flow. Calming chambers are especially useful in certain phases of research and testing as in combustion research, where it is necessary to eliminate all effects of turbulence. While the simplest type of calming chamber is a long tube, more complex types are often employed. Guide vanes of various sizes and configurations are commonly used. Calming chambers are used primarily with a gas as the flowing fluid as compared with liquid flow through a cavitating Venturi.

Instead of calming a flow, it may be required to induce a pulsation or vibration in the flow. For example, in the study of combustion stability in rocket motors it is sometimes desired to simulate the actually experienced fluid line vibration on the hydraulic flow stand. Sonic vibrations may be introduced in a fluid by the simple expedient of coupling a loudspeaker movement to a diaphragm in touch with the fluid; lower frequencies and higher amplitudes are more difficult to obtain. Multi-cylinder piston pumps (Fig. 10), as well as special valves have been used with moderate success. These valves may be high response, electrically operated valves or rotating disk valves. They may be designed to interrupt a

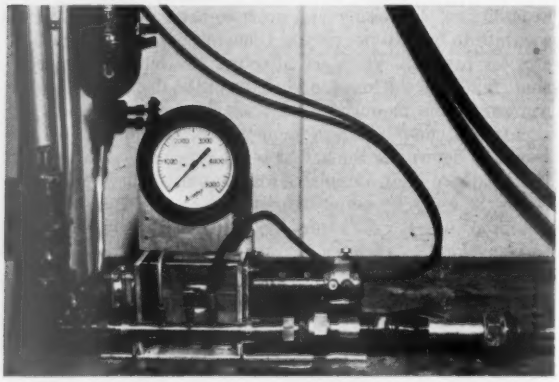


FIG. 10 HYDRAULIC OSCILLATOR, VARIABLE SPEED D-C MOTOR DRIVES A VICKERS, INC., HYDRAULIC PUMP WHOSE PULSATIONS ARE DETECTED BY PRESSURE PICKUPS. THE FLUID PULSATIONS MAY BE COUPLED TO A PROPELLANT FLOW SYSTEM. MAXIMUM FREQUENCY, 700 CPS

continuous flow or periodically introduce or subtract flow to a main conduit. Single pulse devices are also required in certain research cases. The application of the ordinarily unwanted water hammer effect has proved to be successful. A fast closing valve has been used in a by-pass line to produce high amplitude pulses in propellant lines which are then recorded on oscilloscope traces. The chief difficulty of all the existing methods lies in the unpredictability of the amplitude and wave form.

Flow Systems

Figs. 11 and 12 show a schematic diagram and photograph of a typical rocket motor test cell. The fluid systems involved, both liquid and gaseous, perform several functions. The gas system provides a source of pressure for the purpose of actuating the propellant valve or valves and the other fluid actuated valves. The purge system provides a means of cleaning the system of propellants after a firing. The tank pressurizing system is used to pressurize the propellant tanks so that the propellants will flow through the propellant system to the motor.

The functions and relationships of these various systems can be demonstrated by describing the sequence of operations which are involved in a test firing. Only the main points will be emphasized, since various preliminary and secondary operations would serve only to confuse the issue.

When the tanks have been loaded with propellants, gas source pressure (usually nitrogen) is available, and when all liquid lines have been bled of trapped air, the test engineer pressurizes the valve actuator system and the purge system with the available gas source pressure. This is accomplished by the manipulation of the hand-operated loaders on the operator's panel which pressurized the regulator valves in the test cell. The tank propellant valves are then opened to

[4] Numbers in parentheses refer to the Bibliography at end of the paper.

provide a clear passage to the stand propellant valves. The propellant tanks are then pressurized to the proper values by similarly manipulating panel loaders. The reason for this order of pressurization is to permit the operator to have the cell under control at all times, i.e., to permit the venting of the tanks, the dumping of propellants, or the operation of the necessary valves for the averting of a possible disaster. All the gas lines are then pressurized up to the 3-way solenoid valves, which, when energized, will allow the various propellant valves, normally closed, to open. (The propellant tanks are pressurized, and it remains for the propellant valves to be actuated so as to fire the rocket.)

If the firing test is to be conducted with a "propellant" valve, then previous to pressurizing the tanks, the fuel and oxidizer tank and stand valves would be opened. If the test is to be operated without a propellant valve, the fuel and oxidizer stand valves serve as propellant valves. These are mounted as closely as possible to the motor. In either case, fuel and oxidizer tank valves are also installed as safety devices to permit cessation of flow of propellants in case of a fire or explosion at the motor.

With some propellant combinations, it is required that one propellant be injected before the other. In these cases, a

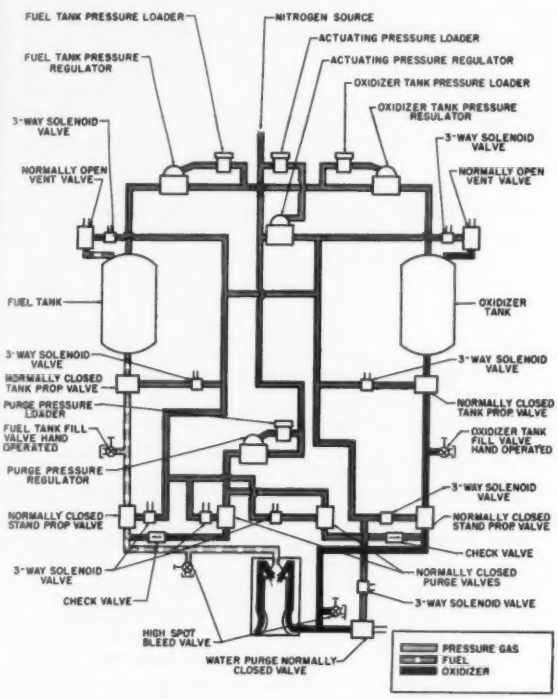


FIG. 11 ROCKET TEST CELL FLOW DIAGRAM

purge solenoid valve is energized, permitting gas to flow initially in the pipe of the propellant which is to be introduced last. This, of course, is a safety measure designed to eliminate the possibility of the first propellant entering the lines of the second propellant. When using a propellant valve, the above procedure is not necessary since the valve would be designed to permit an automatic oxidizer or fuel lead and at the end of the firing, an "over ride."

The first propellant is introduced by energizing the proper solenoid valve which permits the opening of the stand valve. An instant later the other propellant is introduced by the same method, and the rocket motor is firing.

When the firing is terminated, the procedure is opposite to that of the starting operations. If a single propellant valve is used, then the shutdown sequence is accomplished automatically by the proper adjustment of the valve. Without the use of a propellant valve, the oxidizer and fuel valves must

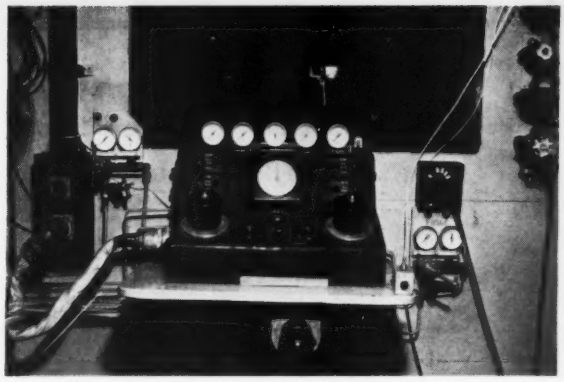


FIG. 12 ROCKET TEST CELL PANEL SHOWING HAND-OPERATED LOADERS, GAGES, SOLENOID VALVE SWITCHES

be properly sequenced by the test engineer and the lines are immediately purged after shutdown. After the motor ceases firing, the hand-operated regulator valves are cranked down, and tank pressure, purge pressure, and actuating pressure are vented. Finally all switches are returned to neutral and the master switch is opened.

Conclusions

The advent of rocket propulsion has greatly increased the number and types of flow control devices required for power plant research and operation. Within the last few years designers have often found it necessary to design and build their own control devices; however, manufacturers of commercial equipment have responded quickly to the increasing need for specialized flow control units. It is now possible to obtain commercially many of the controls described in this article. In the case of some missile applications, severe weight, space, and reliability requirements preclude the use of commercial, units. In this case, home-made units have filled the gap.

The application and design of flow controls have become a significant part of the rocket power plant technology. Despite the greater specialization within this field, it is increasingly important for the engineer to have at least a working knowledge of the function of the many controls required. This is especially true since even the simplest rocket engine is only as reliable as its flow control components.

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REPRESENTATIVE COMMERCIAL SOURCES

(*A*) Alloy Steel Products Company, Inc.
Associated Valve and Engineering Company
American Screw Products
Hydro-Aire Company
James-Pond-Clark Company
Parker Appliance Company
The Weatherhead Company

(*B*) Grove Regulator Company
Gladden Products Corporation
Waterman Engineering Company
Victor Equipment Company
Vickers, Inc.
United Aircraft Products
American Instrument Company
Air Reduction Sales Company

(*C*) Alloy Steel Products Company
Crane Valve Company
Hancock Valve Company
Jenkins Company

(*D*) Annin Company
Marotta Engineering Company
Weston Hydraulics Ltd.
General Controls, Inc.

(*E*) Black, Sivalls and Bryson

(*F*) Greer Hydraulics, Inc.
Vickers, Inc.

(*Continued on page 185*)

Technical Notes

Flow at Constant Volume

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RECENT attention to isothermal expansion (1)[2] and mention of underwater, jet-propelled vehicles (2) suggest that another "classical" thermodynamic process path may be of some interest, namely, the isovolumetric process. In considering an "expansion" at constant volume, it might be noted that nature has already utilized the mechanism in the jet propulsion apparatus of the Squid.

Nomenclature

dq = increment of heat energy
E = internal energy
F' = free energy
P = free stream pressure
V = mean fluid velocity
v = specific volume
γ = ratio of specific heats

Subscript

c = chamber or initial

Following as closely as possible the reasoning of Seifert and Altman (1), we may combine the energy and momentum equations to get (cf. Equation [3] of Ref. 1)

$$d(E + Pv + {}^1/_2V^2) - dq = 0 \quad [1]$$

From the first law ($dq = dE + P\,dv$), but at constant volume

$$dq = dE \quad [2]$$

Now combining [1] and [2] and integrating, give

$$Pv + {}^1/_2V^2 = \text{const} \quad [3]$$

compared with the adiabatic case (cf. Equation [6] of Ref. 1)

$$H + {}^1/_2V^2 = \text{const} \quad [4]$$

and the isothermal case (cf. Equation [5] of Ref. 1)

$$F' + {}^1/_2V^2 = \text{const} \quad [5]$$

Now noting that $P = P_c$ when $V = V_c$, [3] becomes after rearranging

$${}^1/_2V^2 - {}^1/_2V_c^2 = P_cv_c[1 - (P/P_c)] \quad [6]$$

which can be compared with adiabatic and isothermal cases, respectively (cf. Equations [11] and [10] and Equation [7] of Ref. 1)

$${}^1/_2V^2 - {}^1/_2V_c^2 = P_cv_c\frac{\gamma}{\gamma - 1}\left[1 - \left(\frac{P_c}{P}\right)^{(1-\gamma)/\gamma}\right] \quad [7]$$

$${}^1/_2V^2 - {}^1/_2V_c^2 = P_cv_c \ln (P_c/P) \quad [8]$$

It can be noted from the foregoing analysis that the isovolumetric case is also, ideally, at constant temperature and entropy.

Quite obviously the constant volume expansion gives lower efflux velocities under equivalent conditions than does either the adiabatic or isothermal cases. Unlike the isothermal case, the isovolumetric "nozzle" (which is always convergent) will not gain appreciably in performance for a Pc/P ratio greater than around 10 (assuming constant Pc).

Equation [6] is, of course, usually arrived at from the Bernoulli equation for incompressible flow. By following Seifert and Altman's method in this derivation, the similarities in the three processes are possibly more interesting and obvious.

Received December 12, 1952.

[1] Analytical Engineer. Student Member ARS.

[2] Numbers in parentheses refer to the References at end of the note.

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1 "A Comparison of Adiabatic and Isothermal Expansion Processes in Rocket Nozzles," by H. S. Seifert and D. Altman, JOURNAL OF THE AMERICAN ROCKET SOCIETY, vol. 22, May-June, 1952, pp. 159–161.

2 "Morphological Features of the Isothermal Conversion of Chemical Energy Into Propulsive Energy," F. Zwicky, JOURNAL OF THE AMERICAN ROCKET SOCIETY, vol. 22, November-December, 1952, pp. 339–342.

Comment on "The Effect of Variable Propellant Density on Rocket Performance" by H. S. Seifert[1]

ARTHUR S. LEONARD[2]

University of California, Davis, Calif.

IN HIS paper Seifert proves that, in an idealized rocket fixed volume and zero final mass, the replacement of any part of the propellant by an equal volume of a much denser but inert diluent and the uniform mixture and use of this diluent with the rest of the propellant charge can result in a reduction only of the final velocity of the rocket. He also shows that, in an aircraft take-off booster rocket of fixed total volume, the similar replacement and use of part of the propellant can result in a very substantial increase in the final velocity (at the end of burning) of the aircraft and empty rocket. From the title and subtitles of his paper the implication is made that these proofs are theoretical analyses of special cases of the variable propellant principle that was described by the writer in an early issue of the JOURNAL.[3]

What is meant by a "variable propellant" is a combination in which the mixture ratios of the various components change throughout the burning period. By this definition, Seifert does not treat a variable propellant, but instead shows the relative performance that will be obtained with the use of different members of a family of "constant" propellants. The analyses presented and conclusions reached should not, therefore, be taken to apply to a true variable propellant.

Basically, a variable propellant will involve the use of two or more distinctly different propellant combinations, burned in a continually changing ratio. Where increased rocket performance is the reason for going to a variable propellant, the two combinations will usually have widely different densities. One of the propellants may even be a dense inert substance such as mercury. Where one component of a bipropellant is much denser than the other, limited use of the principle may be made merely through the use of a variable mixture ratio.

Since the best propellants of high density have relatively low

[1] JOURNAL OF THE AMERICAN ROCKET SOCIETY, vol. 22, July-August 1952, pp. 213–215.

[2] Specialist, Department of Agricultural Engineering. Member ARS.

[3] "Some Possibilities for Rocket Propellants," by A. S. Leonard, JOURNAL OF THE AMERICAN ROCKET SOCIETY, Dec. 1946, no. 68, pp. 12–16.

EDITOR'S NOTE: This section of the JOURNAL is open to short manuscripts describing new developments or offering comments on papers previously published. Such manuscripts are published without editorial review, usually within two months of the date of receipt. Requirements as to style are the same as for regular contributions. (See inside back cover.)

exhaust velocities, and vice versa, the programming of the propellant ratio so as to make the best use of the principle will involve starting burning with a blend of relatively high density but low exhaust velocity, and gradually changing the mixture ratios throughout the burning period, ending with a combination which possesses a relatively high exhaust velocity but low density.

The most promising field of application of the principle appears to be in getting the greatest possible range or altitude out of a single-step unboosted rocket, such as the V-2. In multistep or boosted rockets, the general idea of the variable propellant can be applied and the advantages obtained by using different but constant propellants in the different steps.

Comment on Variable Propellant Density

HOWARD S. SEIFERT[1]

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IT SEEMS desirable to clarify certain points concerning the paper "The Effect of Variable Propellant Density on Rocket Performance," by H. S. Seifert.[2] Interest in this topic was stimulated by A. S. Leonard's paper,[3] "Some Possibilities for Rocket Propellants." The writer of this note did not understand the argument presented in Mr. Leonard's paper well enough to feel completely convinced by it, so the topic was re-discussed in the writer's own notation. It was only after the new discussion appeared that the present writer realized that Leonard was discussing a *time-varying* program of propellant density, whereas Seifert was discussing the behavior of systems where density remained *constant in time*, but varied from one member to the next of a family of similar rockets.

Any implication that the results of Seifert's paper contradict those of Leonard's is, therefore, withdrawn. The two extreme cases discussed by Seifert (very high and very low mass ratios with density constant in time) represent special cases of the more general physical situation qualitatively described by Leonard.

Received January 30, 1953.

[1] Staff engineer. Member ARS.

[2] JOURNAL OF THE AMERICAN ROCKET SOCIETY, vol. 22, July–August 1952, pp. 213–215.

[3] JOURNAL OF THE AMERICAN ROCKET SOCIETY, Dec. 1946, No. 68, p. 12.

Flow Controls

(*Continued from page 183*)

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2 "Rocket Motor Hydraulics," by G. P. Sutton, *Machine Design*, vol. 22, May 1950, pp. 86–91.

3 "The Closed Circuit Hydraulic System for Aircraft Applications," by C. L. Sadler, *Applied Hydraulics*, November 1950, pp. 24–26.

4 "Environmental Testing of Aircraft Hydraulic Systems," by F. B. Cole, Jr., *Applied Hydraulics*, vol. 4, August 1951, pp. 50–52, 54–55.

5 "Danger Spots in Hydraulic Circuits," by R. Tyler, *Applied Hydraulics*, vol. 4, September 1951, pp. 50–51.

6 "Details of British 'Snarler' Revealed," *Aviation Week*, vol. 55, October 29, 1951, p. 36.

7 "Valve Control of Liquid Flow," by R. Milham and A. R. Catheron, *Instruments*, vol. 25, May 1952, pp. 596–598.

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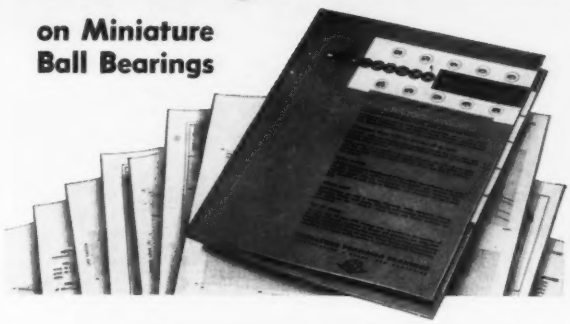

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Rockets Behind the Iron Curtain

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DATA and clues on rocket activities behind the Iron Curtain have been collected by the author over a period of about a year. When examined individually, each piece of information found in American or foreign literature does not reveal any direct trend; however, when all the reports are reviewed as a whole, one can obtain a discernible and definitely disturbing picture of Soviet rocket effort.

It should be realized that the references to Russian rocket work are fragmentary and of questionable reliability. Some of the data, believed to be unreliable, have been eliminated as sources of information, while other data have been expanded by interpretations of the author.

It is quite possible and even probable that some of the clues which have leaked through the Iron Curtain are false and were deliberately planted to mislead Western rocket engineers, researchers, and military experts. Therefore, it is difficult to obtain a true picture of rocket developments in Russia, and the conclusions reached in this paper must be viewed as being quite tentative and even speculative in nature.

The author intends to continue his private investigation of this subject and would appreciate learning of additional information.

Background of Russian Rocket Work

Reliable technical information is available on early Russian rocket research which has been reported previously by several historians and will not be reiterated here. This work probably has little influence on today's Russian rocket developments, but it shows clearly that the Russians had a very early start in this field, and that they displayed independent and fertile technical thought. Most notable among early Russian rocket researchers was Professor K. E. Ziolkowsky, who in 1903 proposed a liquid-propellant rocket engine in an article dealing with the possibility of space travel (1).[2] He was the first to present a mathematical flight theory, and he also proposed oxygen and hydrogen as rocket propellants.

According to German Intelligence, during World War II, active rocket research work was carried out by Ziolkowsky and his associates in a suburb of Moscow. When the German Army approached Moscow, this rocket center was abandoned and the work supposedly was transferred to Sverdlowsk in the Ural Mountains (2). At the captured research site the Germans found housing and foundations identifiable with rocket work, but found no rocket hardware or technical material. These Intelligence reports are evidence of organized, systematic rocket research and development by the Russians prior to and during World War II.

Interest in rockets was sufficiently high that notable classics, such as the original books by Eugen Saenger and M. Vallier, were translated into Russian. Furthermore, during the 1930's and 1940's, books by several Russian authors, such as Perel'man (3) and Langemak (4), were published on the general subject of rockets.

Research and Development Capacity

The development of rockets, as well as any other complex technical device, requires research facilities and the services of highly trained specialists. The Soviets have made great progress in improving their technical and educational facilities. Czarist Russia had only 68 institutions of higher learning, with an enrollment of 112,000. In 1941, Russia had 800 such institutions, with an enrollment of 667,000 (5, 6). New research institutions have been added since 1941.

Results of Russian research in fields related to rockets can be found in many scientific journals. Typical articles on combustion (7, 8, 9), boundary-layer theory (10), and flame propagation (11) indicate continuing activity in the propulsion field.

It is believed that the Russians have the background, the teachers, and the students for competent rocket research and development. Certainly they demonstrated important accomplishments in World War II.

Solid Propellant Rockets

During World War II the Russians put in service several types of solid propellant rockets. In the battle of Stalingrad a new barrage rocket, a new antitank rocket, and new rocket launchers (12) were used in relatively large numbers, and were instrumental in turning the tide of the war against the Germans. It is significant that these rockets were used in the field before solid propellant rockets were used extensively by our military forces, and that the propellants used by the Russians were basically different from ours.

The brief literature survey which preceded the writing of this paper did not yield any significant information concerning recent Russian investigation on solid propellants. However, late Russian scientific publications contain articles on the process control of ammonium nitrate production (13, 14). This chemical is known to be a very cheap oxidizing agent for solid propellants, but its use presupposes control of polymorphic transformations. Since ammonium nitrate has other applications, this work does not necessarily indicate active research on this chemical for use as a solid propellant.

Aircraft Rocket Engines

There are a number of recent articles on the use of auxiliary rockets in Russian military jet-fighter aircraft. These rockets are designed to increase the airplane performance at high altitude and to augment the take-off thrust. During the re-

Presented at the Annual Meeting of the AMERICAN ROCKET SOCIETY, New York, N. Y., December 4, 1952.

[1] Propulsion Supervisor, Aerophysics Department. Member ARS.

[2] Numbers in parentheses refer to the References on page 191.

EDITOR'S NOTE: The information reported in this Section has been selected from approved news releases originating with the Department of Defense, private manufacturers, universities, etc., and from published news accounts in journals and newspapers. The reports are considered generally reliable, although no attempt has been made to verify them in detail.

cent Soviet Aviation Day in Moscow, several fighter-type airplanes were observed which developed smoke trails in flight, possibly from the exhausts of auxiliary rocket engines (15).

Rocket installation on two specific swept-wing Soviet airplanes is mentioned in the literature: the La-17 and the Yak-21 (16, 17, 18, 19). Basic data on these airplanes are shown in Table 1. Other Soviet airplanes are reported to have used rocket assistance, but this discussion will be limited to these two.

TABLE 1 SOVIET FIGHTER AIRPLANES WHICH HAVE USED AUXILIARY BUILT-IN ROCKETS

Airplane designation	La-17	Yak-21
Designer	Lavochkin	Yakolev
Span, ft	36	31
Length, ft	36	21
Flight Mach number	Close to 1.0	Above 1.0
Gross weight, lb	16,000	12,000

The rockets which apparently were installed in these two airplanes were auxiliary engines and were used intermittently. A turbojet engine was the principal power plant. Use of the rocket engine permits an improvement in combat capabilities, such as an increase in speed, rate of climb, or maneuverability. This performance gain can be realized only while the rocket engine is operating. As rockets are notoriously poor in their specific fuel consumption, the airplane must carry a heavy weight of rocket propellant in addition to the fixed weight of the rocket installation. Because of this added weight, the airplane suffers a very considerable performance loss when the rocket is inactive. Consequently, there is a reduction in range, endurance, rate of climb, or radius of turn. Therefore, the claims which have been made in some American publications, that the addition of a rocket improves the range of the airplane, are believed to be wrong.

Some of the references state that only the later versions of the La-17 and the Yak-21 were fitted with rocket units, and that experimental rocket-equipped aircraft were flown as early as 1948. To the best of the author's knowledge, no such rockets had been used in Korea up to the time of writing this article.

There is disagreement among the references as to the details of the Russian auxiliary rocket unit. Some maintain it is a refinement of the German Walter 109-509C rocket unit; others claim it is a refinement of the German BMW 109-718 rocket engine. In either case, it is supposedly an improved and advanced version of some original German work. Table 2 shows some of the characteristics of these two units, and some guesses (by this and other authors) about advanced versions. The original German units are shown in Figs. 1 and 2.

In general, the improved units are reported to have more thrust than their German predecessors. The use of two rocket thrust chambers indicates a climbing-flight or acceleration-flight phase as well as a cruising-flight phase.

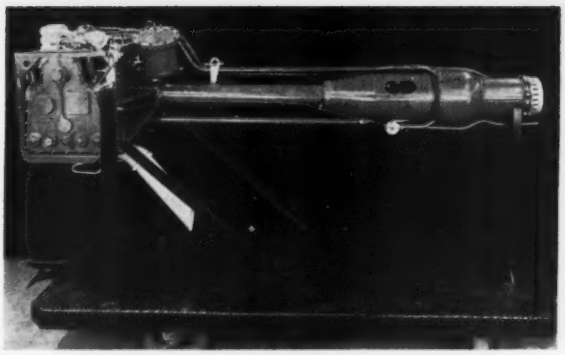

FIG. 1 GERMAN WALTER 109-509C ROCKET ENGINE

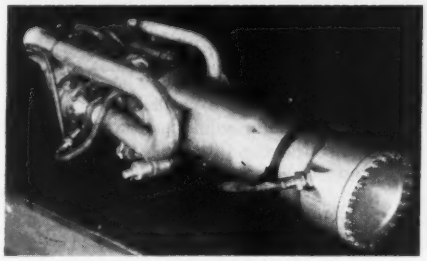

FIG. 2 GERMAN BMW 109-718 ROCKET ENGINE

In their zone of Germany the Russians have the rocket facilities of BMW (Bayrische Motoren Werke) near Berlin, and several German air bases which used the Walter rocket engine. Soviet military and technical missions have used these facilities to their advantage, and probably know all they care to know about these two German rocket engines. They have had the cooperation of German engineers. They have had time to use German rocket engines in flight tests on Russian airplanes. It is reported (16) that experimental rocket installations were made and tested on piston-engine airplanes such as the La-7 or La-9 fighter. Early results must have been sufficiently encouraging to justify further development and installation of rocket engines on high-speed fighters such as the La-17.

The estimated weights in Table 2 show the extra penalty which must be carried by the airplane for an arbitrary 2 minutes of rocket operation at 30,000-ft altitude. For example, because the Kostikov unit of 6000-lb thrust is so heavy, it is doubtful that serious consideration would ever be given to this unit for use as an auxiliary engine in a turbojet driven airplane. If the information of Ref. 16 is reliable, this rocket engine would probably be used as the principal power plant of an aircraft which is powered solely by rockets and which has a very short flight duration and range.

From all the evidence, it can be concluded that the Soviets have had in operation some fighter-borne liquid-propellant

TABLE 2 GERMAN AND POSSIBLE RUSSIAN-IMPROVED AUXILIARY ROCKET ENGINES

	Unit			
	German Walter 109-509C	German BMW 109-718	Suggested improved Walter unit	Suggested improved BMW unit
Manufacturer or designer	H. Walter, Germany	BMW, Germany	Unknown, Russia	Kostikov, Russia
Oxidizer	Hydrogen peroxide	Nitric acid	Hydrogen peroxide	Nitric acid
Fuel	Mixture of alcohol, hydrazine hydrate, and water	50% xylidine, 50% triethylamine	Unknown	Gasoline
Mixture ratio	3.33	3.5	Unknown	Approx. 4
Thrust rating, lb	440–3700	2200 (later 2600)	4500	6000
Pump power supply	Gas generator and turbine	Shaft from jet engine	Gas generator and turbine	Gas generator and turbine
Weight of engine, lb	368	115	140–250	150–240
Propellant required for 2 min, lb	2140	1500	2600	3460
Number of thrust chambers	2	1	1 or 2	1 or 2

auxiliary rocket engines. It may be that their experience has been so discouraging that they have abandoned or delayed the use of auxiliary rockets in fighter airplanes; or perhaps they have developed a highly potent weapon which, in typical Russian fashion, they are saving for the day when they really need it. These fighter-borne liquid-propellant rocket engines are probably a Russian development, and not simply an extension of German efforts.

One recent source (20) indicates that the Russians are experimenting with vertical take-off and landing of fighter airplanes. The aircraft is stood up on its tail and launched by rocket power. Landing is accomplished by parachute and rocket control. This method of putting fighters into the air has the advantage of eliminating the need for landing fields. Thus, a fighter defense system becomes easy to hide and less vulnerable to bomber attack.

Liquid Propellants

The Russians are reported to have chosen nitric acid and gasoline (or kerosene) as liquid propellants for some aircraft applications. The use of gasoline has the logistic advantage of using essentially the same fuel for the jet engine and the rocket. The Soviets have succeeded in solving the problem of ignition (16). However, they still are faced with the difficulty of handling a very corrosive liquid (nitric acid) inside of an airplane, and they undoubtedly have had to develop special techniques and procedures to cope with this problem.

Other references indicate that research has been done on the combustion of oxygen with benzene (21) and on the spontaneous ignition of aldehydes with oxygen (22). This interest in combustion with oxygen may be connected with their Soviet rocket work, or it may be an extension of the work done by a Russian group on the chemical kinetics of the oxidation of hydrocarbons. Men like Semenoff and Zeldovich pioneered in this field in the early 1930's. This work on oxygen, and some fundamental studies on the pumping of low-temperature liquids (23), indicate that the original German work with liquid oxygen may have been improved by the Russians. For long-range missiles the emphasis definitely seems to have been placed on oxygen and kerosene (2).

Guided Missiles

At the end of World War II the Germans, with their development of the C-2 "Wasserfall" antiaircraft missile and their V-2 long-range weapon experience, were far advanced in the field of guided missiles.

Although the United States has obtained many eminent German scientists, the Russians captured almost all of the rocket experimental and production facilities and probably sufficient technical personnel to operate them.

It is known that the Russians activated the German V-2 manufacturing facilities (Mittelwerk, near Nordhausen) and, shortly after the end of World War II, had them in operation at a reduced rate of production. Now what have they done with all the V-2 missiles which they captured and have produced?

1 They probably have used some for basic scientific explorations, such as upper-atmosphere research, aerodynamic investigations, radiation research, photography developments, parachute tests, and many other studies similar to our operation at White Sands, N. Mex. (24).

2 They probably have used some to train troops in the operation of guided missiles. The Germans used several hundred V-2 missiles for this purpose before they fired the first missile at England.

3 They probably have used some to investigate improved rocket power plants and new warheads, and thus have laid the foundation for future improved missiles.

4 They could have stockpiled V-2 missiles for a possible future conflict. Some reports indicate that the Russians have made considerable preparation to establish bases from which to launch V-2's in large numbers against European targets (5, 25).

5 They could have used some for developing a V-2 of improved accuracy, higher payload, or longer range. This could imply increasing the specific thrust above the original sea-level value of 203 sec, or increasing the thrust of the rocket above the original sea-level design value of 56,000 lb. Some of the oxygen research work reported above indicates possible improvement of this type, and one source (2) indicates that the Russians are working on an improved V-2 missile engine with a 35-metric ton (77,000-lb) thrust.

No matter which of these five uses they chose, they have undoubtedly profited from the experience and from having a ready-made production line fall into their hands. The V-2 has provided them with missile production knowledge and with a weapon which can deliver a warhead of 2200 lb in a range of 220 miles (or more, if they have improved the missile). A recent report (26) claims that missiles have been launched at Kohlberg (near Stettin, Germany) and directed at the Island of Ezel (in the Baltic Sea), which is approximately 400 miles from Kohlberg. If this report is correct, the V-2 has been improved significantly. The Germans had tested a few winged versions of the V-2, which supposedly were designed for over 400-mile range. It is possible that the reported long-range weapon of the Russians is a winged version of the V-2 (called A-9 by the Germans), or that it is a more highly powered V-2 without wings. A German A-9 missile is shown in Fig. 3.

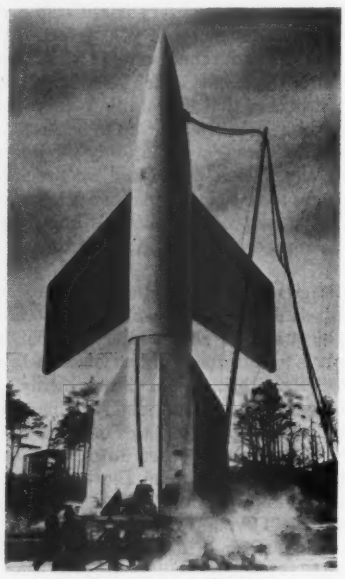

FIG. 3 GERMAN A-9 MISSILE

The German C-2 Wasserfall guided antiaircraft missile is another weapon which fell into Soviet hands. It was almost completely developed by the Germans during World War II, but lacked a satisfactory guidance system. Several completed missiles and the pilot plant for this missile are known to be in Russian possession. It is more than likely that they have worked out a guidance and control system in the last seven years, and that they are producing this C-2 missile or an advanced version. If they have met the original German specifications (Table 3), the Soviets now have a very potent antiaircraft weapon.

The German "Taifun" rocket, a liquid-propellant, unguided antiaircraft weapon, also fell into Russian hands. It is quite possible that either the C-2 or the Taifun missile, or a Russian equivalent, has been adopted for the defense of Soviet Navy

TABLE 3 ORIGINAL GERMAN SPECIFICATIONS FOR THE C-2 ("WASSERFALL") ANTIAIRCRAFT MISSILE

Proximity of warhead to target for effective destruction, ft	200
Maximum target altitude, ft	30,000–50,000
Target speed, mph	400
Minimum missile storage life (ready to launch), yr	1
Storage temperature limits, °C	−20 to 55
Warhead weight, lb	220
Maximum missile maneuver acceleration, g	10
Rocket thrust, lb	17,600
Rocket duration, sec	45
Oxidizer	Nitric acid
Fuel	Vinylisobutylether
Missile take-off weight, lb	7500–8500

vessels against air attack. Reports indicate the use of such weapons by the 35,000-ton aircraft carrier Sovetsky Soyush and by 40,000-ton battleships of the Sovetoki Soyuz class (25, 27). One source (28) reports the development of a new type of missile which is launched from submarines.

Another source (2) reports three other new missile developments. Two of these are large missiles requiring high-thrust rocket engines. The first is a two-stage, long-range missile, with an ultimate range of 3000 kilometers. Data on this development are given in Table 4. The second is a single-stage, winged missile which uses the same rocket power plant. The rocket engine is interesting and unusual, because the thrust is higher than any other previous value published in the literature and because chamber pressure is high for conventional rocket practice. Since the propellants are supposedly liquid oxygen and kerosene, this development is not merely a straight extension of German V-2 work, for the Germans used alcohol as a fuel.

TABLE 4 RUSSIAN LONG-RANGE TWO-STAGE MISSILE

Range (eventual ultimate goal), km	3000 (1865 miles)
Probable gross weight, lb	150,000–175,000
Second-stage type	Modified German V-2
Second-stage thrust, metric tons	35 (77,000 lb)
First-stage type	New Russian design
First-stage thrust, metric tons	120 (264,000 lb)
Chamber pressure, atm	60 (882 psi)
Rocket-engine weight, lb	Under 6600
Specific impulse (sea level), sec	240
Oxidizer	Liquid oxygen
Fuel	Kerosene

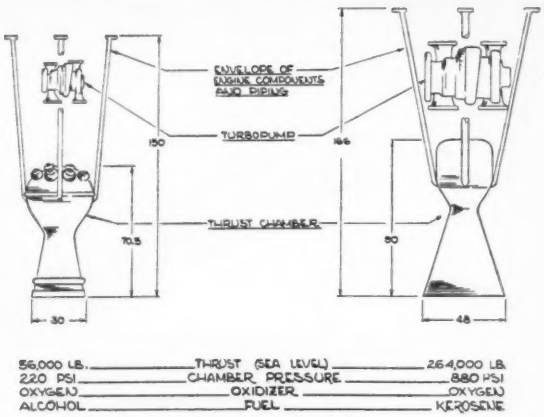

FIG. 4 COMPARISON OF RUSSIAN 120-TON ROCKET ENGINE AND GERMAN V-2 ROCKET ENGINE

The development work supposedly was conducted in part at Khimki near Moscow. A comparison of this reported Russian rocket with the German V-2 is given in Fig. 4.

The third new development is a small tactical missile with a range of 35 to 40 miles. It has a thrust of 17,600 lb.

Testing and Production Facilities

With few exceptions, all of the rocket facilities built by the Germans are in the Russian Zone of Germany (Fig. 5). The famous German rocket development center at Peenemuende is reported to be back in operation, and at least four different German missiles are reported to be in production (28, 29).

During World War II, along the Baltic Sea coast from Peenemuende toward Lithuania, the Germans built a fine launching range for V-2 missiles, complete with a number of launching ramps, radar and photographic observation stations, salvage- and patrol-boat stations, airfields, and anti-

FIG. 5 SOVIET ROCKET FACILITIES

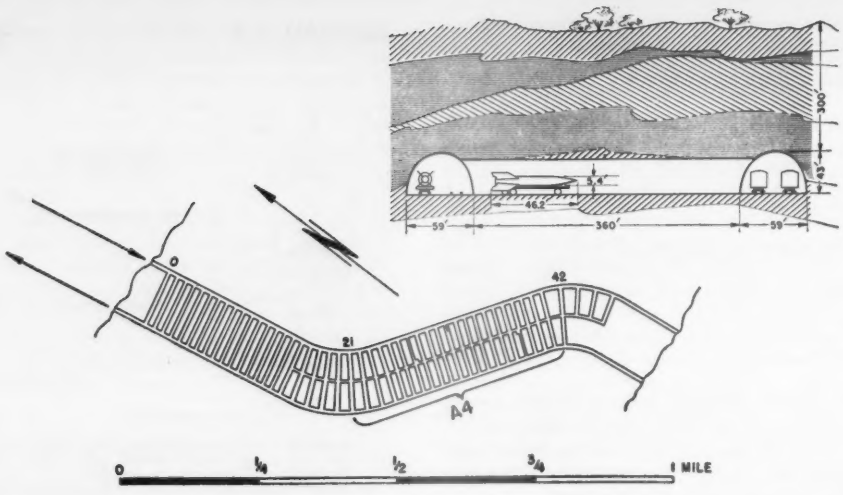

FIG. 6 LAYOUT OF GERMAN V-2 ASSEMBLY PLANT, MITTELWERK, 1944–1945

aircraft defenses. It is this region that supposedly has been used by the Russians for long-range missile flights (6), and they have displayed great concern about keeping aircraft and travelers away from this area. However, it is not very likely that the Soviets are actively using Peenemuende or the Baltic Sea launching range. In the first place, these facilities are strategically poorly located, as they are within easy bombing range of potential enemy bases. Secondly, there is the possibility that a poorly fired missile might land on Swedish or Danish territory. The Russians would not cherish the thought of their missile secrets falling into the hands of even a neutral country. Thirdly, there are several regions within the boundaries of the Soviet Union which do not have these disadvantages and which have a more favorable climate than the Baltic area. The regions of the Kirghiz Steppe or the Gobi Desert would provide a superior launching range, particularly since the missiles would fall on the ground and would not be lost in the sea.

The German V-2 production facility at Mittelwerk was an advanced, bombproof plant which has been reactivated by the Russians. Because of the facility's unusual features (e.g., bombproof, underground construction), a sketch of the layout is shown in Fig. 6.

One source (5) locates a rocket-engine factory at the Moscow airport and credits Professor N. Kostikov with having been a prominent rocket researcher in the Soviet Union. Other rocket factories are supposedly located in the interior of Russia, and such men as Petrovich and Shershwesky are supposedly prominently connected with this work.

Space Travel

The Russians have had an active interest in rocket-propelled spaceship ever since the days of Ziolkowsky. There has been recent evidence that their interest is not merely academic. A pronouncement by Dr. M. K. Tikonravov in the newspaper *Pioneer Pravda* discusses various aspects of and calculations on travel to the moon (30). He estimates that a moonship capable of carrying two men, circumnavigating the moon, and returning to the earth, would have a take-off weight of 1000 metric tons. He estimates that, to establish an intermediate artificial satellite, the spaceship need weigh only 100 metric tons.

In the Soviet magazine, *The Red Fleet*, there is reported to be an article dealing with the planning of a Soviet moonrocket (31). It is supposed to be 183 ft long and 45 ft in diam, to weigh 1000 metric tons (2,200,000 lb), and to be powered by 20 rockets with a capacity of 350-million horsepower.

Assuming a thrust-to-weight ratio of approximately 2, these data indicate that the Russians are planning or working on a rocket engine of approximately 220,000-lb thrust, and propose to use an engine cluster of 20 such rockets. Presumably this is the same rocket engine of 120-ton thrust which was discussed in a previous section.

Various missile calculations led H. Koelle to the conclusion that this reported Soviet moonrocket is suitable for transporting a small payload (perhaps 660 lb) around the moon and back (32). He does not believe that a manned moonrocket can be realized by the Russians within the foreseeable future. However, he admits that a pilotless moonship, though a huge technical project, is possible of realization and would have enormous psychological and propaganda value, because a successful flight would demonstrate without doubt the ability of the Soviets to send long-range rockets to any point on the globe.

Evidence of advanced thinking can be found in Russian articles dealing with satellites, television observation from satellites, and atomic rocket engines (33).

Conclusion

While this discussion has been devoted to specific Russian rocket developments, some interpretation of the basic Soviet attitude on disclosing new weapons is in order. It seems that they will not disclose or use new armament devices unless they are losing a war. In Finland, Spain, Greece, and Korea, Soviet or Soviet-supported forces have traditionally and repeatedly put old, outdated armament and equipment in the field, expended poorly equipped troops, and used outmoded airplanes. For example, the MIG-15 jet airplanes in Korea are often reported to be second-rate fighters if compared to newer Soviet aircraft. Only when World War II was going badly for them did the Russians put several new fully equipped armored divisions into battle, and unveil new tanks and new armament rockets. Any potent new rocket developments or new powerful rocket weapons will probably be closely guarded and kept secret until the Soviet armies are suffering reverses. Therefore, it is doubtful that any basically new rockets will be used in Korea, other than perhaps Russian counterparts of any United Nations rocket weapons which are put into war service. For this reason, it probably will be a long time before the full story of Soviet rocket development will become known.

The clues to Soviet rocket development which are reviewed here are meager and of questionable reliability. Nevertheless, they indicate that the Soviets have a good foundation and background in the science and engineering of rockets.

TABLE 5 SUMMARY OF IMPORTANT RUSSIAN ROCKET DEVELOPMENTS

Rocket type	Thrust, lb	Duration, min	Application	Status (1952)
Aircraft auxiliary engine (liquid propellants)	2,000–6,000	1–3	Assisted take-off and superperformance of fighter aircraft	Some German units flight tested prior to 1948. Advanced design probably developed since 1948
Pressurized liquid-propellant rocket	10,000–20,000	0.5–1	Antiaircraft missile	Improved German C-2 ("Wasserfall") probably in production
Liquid-propellant high-thrust engine	56,000–77,000	1	V-2 type guided missile	V-2 was in production following World War II. Improved model probably now in production
Liquid-propellant high-thrust engine	264,000	1 plus	(1) Single-stage ballistic missile (2) Long-range (1800 miles) two-stage missile (3) Planned for use in satellite vehicle	Engine currently under development
Solid-propellant rocket	Unknown	Unknown	(1) Assisted take-off (2) Aircraft armament rocket (3) Antitank rocket (4) Barrage rocket	Unknown; probably fully developed
Medium-thrust rocket engine	17,600	Less than 1	Short-range (60 miles) missile	Possibly a modified version of the "Wasserfall" missile, a miniature version of the V-2. Probably fairly well developed

They have demonstrated some capabilities in this field and undoubtedly are working, or have worked, on advanced aircraft rocket power plants, on rocket-propelled missiles, and on high-thrust large rockets for long-range missiles or satellite vehicles. They have had the good fortune to obtain German rocket plant facilities, technicians, and production experience.

The author's interpretations of some important Soviet rocket developments are summarized in Table 5. The available data indicate intelligent and advanced Russian accomplishments in the rocket field. These Soviet developments should not be underestimated.

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Rockets

GRAND Central Aircraft Company of Glendale, Calif., and Tucson, Ariz., has established a rocket division near Pacoima, Calif., for the purpose of developing and producing solid propellant rocket motors. The company has contracted with the U. S. Army Ordnance Corps for the production of an antiaircraft weapon developed by the Jet Propulsion Laboratory of the California Institute of Technology. Grand Central has developed a unique, new-type propellant claimed to have low-flame temperature, low cost, long storage life, and a wide range of operating temperatures. Grand Central also is manufacturing other solid propellants for the military and has designed and developed high performance rocket motors for jet assisted take-off, starters for jet engines, and numerous auxiliary power plant applications for guided missiles. The Pacoima facility is comprised of propellant mixing stations, rocket motor assembly buildings and test areas, warehouses, administration and engineering structures.

NORTHROP Aircraft, Inc., has received U. S. Air Force orders for the production of a quantity of guided missiles. The missile contracts now held by Northrop call for deliveries through 1955. Some indication of the extent of Northrop's contributions in the guided missile field is evidenced by the fact that it now employs approximately 3500 workers in this activity.

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DOUGLAS Aircraft Company's annual report for 1952 indicates that it has put two guided missiles on the assembly line and that its total guided missile production is up 60 per cent over 1951.

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RECENT reports from Europe indicate that ground-to-air rockets for the Red Army are now being manufactured in Poland, Czechoslovakia, and Hungary. The Hungarian units are being produced in a semifinished plant at Cinkota, near Budapest. Some old truck-mounted rocket launchers have been revamped so as to be capable of vertical elevation for firing at air targets. One new model of the launcher with short guide rails has been seen during transit in Poland.

One of the reports claims that Russia now has a successful air-to-air guided missile. The 15-ft long missiles carried under the wings of the MIG-15 were originally thought to be new supersonic wing tanks. During several observed trial runs, the missiles were fired as soon as the planes sighted the target drones. The missiles hit the target drones, and were lowered to the ground by parachutes. As soon as the missiles were fired, the launching aircraft turned through 180 deg and left the point of interception. From this it is concluded that the launching aircraft does not guide the missile, but that the missile carries its own guidance system.

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ACCORDING to Kenneth H. Jacobs, assistant chairman of the Propulsion and Structural Research Department of the Armour Research Foundation, the two prime obstacles to be overcome before pilotless rockets can be sent to the moon are navigation and guidance. Engineers using present-day knowledge are able to construct a successful four-step rocket capable of carrying a 100-lb payload to the moon. According to Jacobs the rocket would be 125 ft long with a gross weight of 400,000 lb. The fourth and final stage would weigh 800 lb including the 100-lb payload. This fourth stage would attain a velocity of 25,000 mph at 782 miles altitude and would then coast to the moon. Mr. Jacobs is also the temporary chairman of the newly organized Chicago Chapter of the American Rocket Society.

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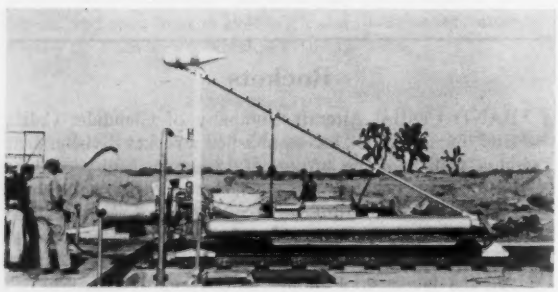

FIG. 1 NORTH AMERICAN AVIATION'S ROCKET-POWERED TEST SLED

A ROCKET engine to streak the world's fastest earth-bound test laboratory (Fig. 1) from a dead stop to 1500 mph in 4.5 sec has been designed and built by North American Aviation for the Air Force. With the test sled, the parachutes, other equipment, instruments, and materials can be checked for high-speed service.

A Highway in the Sky

BY carefully coordinated observation of cloud formations, weather stations across the country could establish the location and direction of the jet stream, a mysterious wind tunnel in the sky, a General Electric Company weather scientist said. Speaking before the American Meteorological Society, Dr. Vincent J. Schaefer recently said that "four specific and rather spectacular cloud types" are visual keys to the whereabouts of this high-speed stream that often doubles the speed of high-flying aircraft.

Field research which he directed last summer as scientific adviser for the Munitalp Foundation, now sponsoring basic research in meteorology, showed that any three of the four tell-tale cloud formations, plus high cloud speeds and "coherent" patterns, may be used to determine the presence of these powerful winds.

At present it takes fairly complicated upper air soundings to locate this skein of winds that blows at speeds of from 80 to more than 200 mph at altitudes of 20,000 to 50,000 ft. The stream moves at slower speeds at lower altitudes.

The four basic cloud formations are: (1) Cirrus streamers, white feathery wisps with tufted trails, seen moving at high speeds and high altitudes. (2) High cirrocumulus—small, white, rounded clouds in patches often scattered at random, but sometimes shifting rapidly to cirrus streamers with delicate wave patterns. They often take on tints of green and red near the sun. (3) Altocumulus, fleecy, nearly stationary formations with lens-shaped clouds, piled layer upon layer at middle altitudes (about 20,000 ft). These clouds change rapidly, especially when sending snow in long streamers down wind. Such streamers are evidence of the high-speed movement of the air. Some of these formations also are tinted near the sun. (4) Billowing altocumulus clouds which often extend from horizon to horizon, with parallel waves running at right angles to the direction of air flow.

Other tell-tale signs of the proximity of the major axis of the stream include: Gustiness at ground level in about half the cases observed; persistent cool, crisp air; generally blue skies, with visibility unlimited; precipitation often limited to "sporadic sprinkles of rain or snow," and rapid changes in cloud cover, from one-tenth of the sky to nine-tenths and back again "in less than an hour."

Quick identification of this phenomenon is becoming increasingly vital to aviation and also to weather forecasting. Studies show that the jet stream shifts about over the northern hemisphere as the seasons change.

This air corridor is blamed for many freak weather conditions believed caused when its undulating path carries polar air to Florida and tropical air masses to the north. Many floods, droughts, and persistent cold and hot spells are attributed to its influence. Dr. Schaefer reported that high winds on New Hampshire's Mount Washington have shown a high correlation with the presence of the jet stream, in preliminary studies made by R. E. Falconer, G-E meteorologist. Dr. Schaefer also has suggested to forestry officials that they investigate effects on forest fires of high winds connected with the jet stream.

Aircraft

THE Finnish Air Force has just received delivery of three deHavilland Vampire 52 jet fighters. Thus Finland has decided to equip its Air Force with the same type of fighter that is operated by Sweden and Norway. The Vampires have been found to operate successfully at the low temperatures (−75 F) encountered in Finland.

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NORTH American Aviation has received orders to build a substantial number of the new F-100 jet fighters for the U. S. Air Force. The airplane, designed to fight at supersonic speeds, will be built at the company's Los Angeles plant.

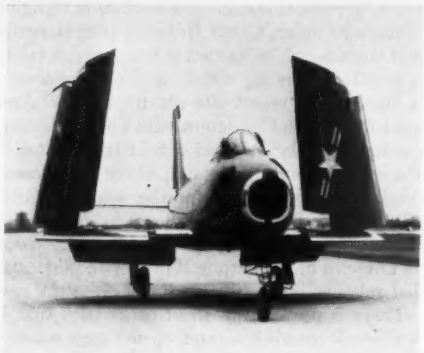

FIG. 2 NORTH AMERICAN AVIATION'S FJ-2 FURY, SWEPT-WING, CARRIER-BASED JET FIGHTER

Due to Air Force security restrictions, no data on the new plane's configuration or performance characteristics can be released.

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THE U. S. Navy has accepted delivery of the first production model of the North American FJ-2 Fury (Fig. 2), 650-mph swept-wing carrier-based jet fighter. The Fury, powered by a G-E J-47-G-E-2 turbojet engine, can operate at 45,000-ft altitude and has a range of about 1000 miles.

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THE French are flight testing a 0.85 Mach jet fighter known as the SE-2415-02 Grognard. This all-weather fighter is unique in that its two Hispano Nene engines are mounted one above the other behind the pilot, giving the plane a camel-like appearance. The Grognard has a span of 51 ft, a length of 55 ft and a height of 19 ft. The experimental version of this airplane has a range of 645 miles with a gross weight of 32,000 lb.

Firebee

RYAN Aeronautical Company with the approval of the Department of Defense has released Figs. 3, 4, and 5 of its pilotless jet target drone, the Firebee. The all-metal aircraft has a span of approximately 12 ft, a length of 18 ft, and a weight of about 1800 lb. The Firebee is currently powered by a Fairchild J-44, 950-lb thrust turbojet. The compact 300-lb engine has a length of 72 in. and a diameter of 22 in.

The near sonic speed recoverable drone is used as a target for modern defense weapons, and is capable of simulating piloted jet plane maneuvers. It is also adaptable for ground-to-air tracking and firing, and air-to-air interception problems.

The Firebee is operated from a remote control station equipped with a small control stick and suitable switches for changing the engine speed and other flight conditions. It can be flown out of sight and at high altitudes.

A two-stage parachute recovery system had to be developed for the drone. The parachutes are capable of lowering the

FIG. 3 SERVICING THE FIREBEE

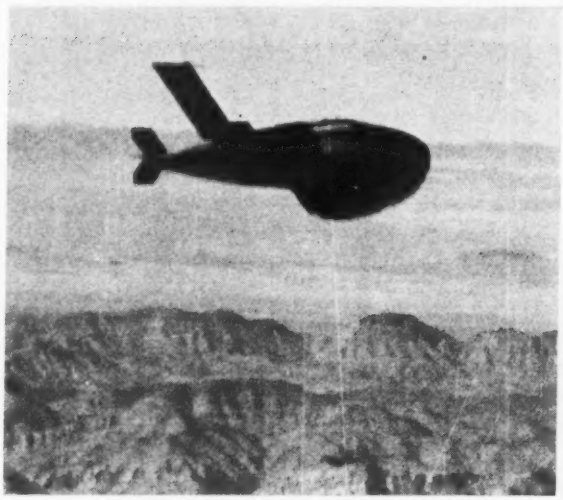

FIG. 4 THE FIREBEE IN FLIGHT

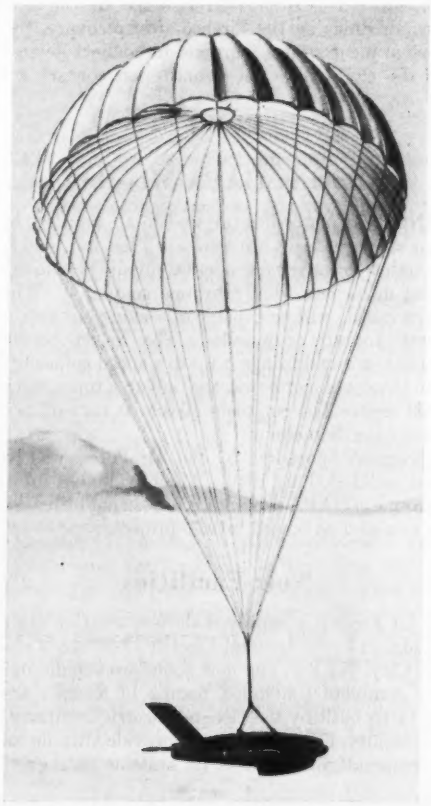

FIG. 5 THE FIREBEE RECOVERY SYSTEM

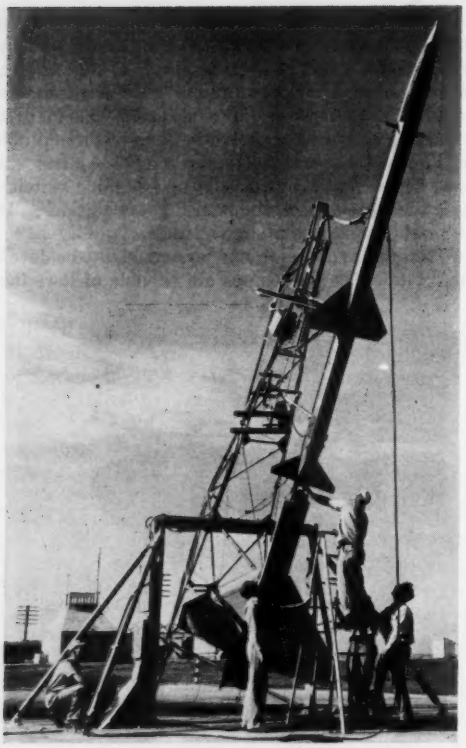

FIG. 6 GAPA MISSILE IN LAUNCHING RACK

Firebee to the ground automatically in the event of a target hit, loss of radio wave carrier from the remote control station, engine failure, or upon command by the remote control operator. In order to prevent damage to the drone by ground winds dragging the Firebee after recovery, the parachute system incorporates a ground disconnect device which detaches the chute from the drone upon contact with the ground.

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Boeing GAPA Missile

BOEING GAPA missiles (ground-to-air pilotless aircraft) in various stages of flight are shown in Figs. 6, 7, and 8. The GAPA ramjet-powered experimental missile is unique in that it is being developed wholly by one company. When perfected, the missile will be capable of seeking out and destroying enemy aircraft or missiles. The rocket booster unit launches the unit and brings it up to a speed sufficient for the ramjet to take over and power the unit to a top speed of more than 1600 mph. The complete missile at take-off is over 26 ft long and has a diameter of 1 ft.

This program, sponsored by the Air Force, was begun in 1945 and concluded in 1949. Much valuable information gained from the GAPA program is now being utilized by Boeing in a new and advanced missile project.

New Facilities

THE Air Force has approved the construction of a million-dollar addition to the General Electric Company's plant near Johnson City, N. Y. The new soundproof building will be used for complete controlled testing of aircraft armament systems being built by the General Electric Company. With this new facility, GE engineers can provide altitude and high- or low-temperature conditions for systems testing.

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ONE of the world's few privately owned rocket test stations devoted to rockets and guided missiles is being built by Hawker Siddeley Group, Great Britain's largest producer of aircraft and engines. It is located in Salisbury, a village near Adelaide, South Australia, within a short distance of the Woomera Range, top secret site set up by the Australian Government for British Commonwealth missile development. The new station will be in effect a field trial center in communication with Coventry, England, where basic research has been carried out since the war at the works of Armstrong Whitworth, Hawker Siddeley subsidiary.

Commenting on this development, H. M. Woodhams, Managing Director of Armstrong Whitworth, said: "Rockets and guided missiles obviously require large open spaces for testing. There is no place in the British Isles that has the necessary climatic conditions and open range requirements. There we plan to carry out exhaustive shooting tests into the strato and ionospheres and beyond."

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IN A SMALL test hangar, Figs. 9, 10, literally chained to the blizzard-swept peak of 6240-ft high Mount Washington near Forham, N. H., prototype jet engines for Air Force and Navy fighters and bomers are given intensive icing tests by General Electric gas turbine engineers.

On Mount Washington, whose summit is stormier than the polar icecap, the wind achieves a velocity of from 75 to 110 mph for four months in the year. Temperatures there have dipped as low as −46 F and the wind has been known to attain a velocity of 230 mph. These subzero temperatures closely simulate conditions that affect jet engines when a plane begins to make its landing approach.

FIG. 7 GAPA MISSILE AT LAUNCHING

FIG. 8 GAPA MISSILE WITH ROCKET BOOST

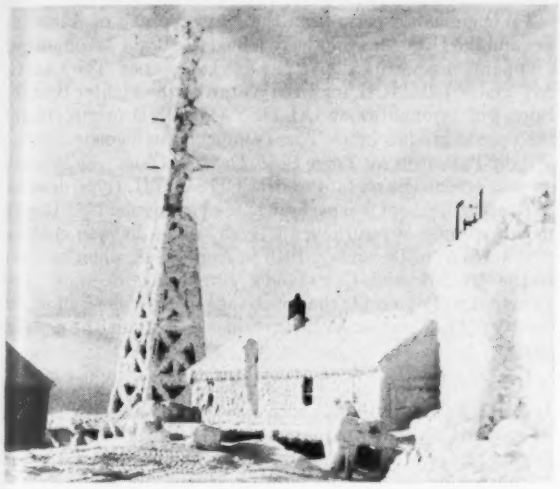

FIG. 9 G-E MT. WASHINGTON GAS TURBINE LABORATORY

Icing conditions affect jet engines when the plane is dropping from 6000 ft to sea level at reduced throttle for a landing approach. In climatic tests run on prototypes of production models, the engineers determine the operating conditions under which the engine will begin to ice up. One important aspect of the test program is the development of new anti-icing devices similar to the "hot nose" used on the J-47-23.

✦ ✦ ✦

AEROJET, under contract to the Corps of Engineers, Mobile District, Mobile, Ala., and in conjunction with the Ralph M. Parsons Company, prepared basic design criteria for a guided missile static test facility and research laboratory to be constructed at Redstone Arsenal, Huntsville, Ala.

A new 36-week contract was recently awarded to Parsons-Aerojet by Redstone Arsenal for the preparation of a design analysis following the approved basic design criteria. This study will provide the necessary engineering solutions to establish the contractual scope for additional contracts covering the engineering and fabrication phases. The intention of Redstone Arsenal and the Corps of Engineers is to negotiate a series of eight contracts before the termination of the current contract. These contracts encompass the complete design and construction of the test facility and will total approximately $12,000,000.

✦ ✦ ✦

FREEZING, a modern new tool of aircraft manufacturing, took on bigness as well as quickness at Lockheed Aircraft Corporation when the company put into operation a cavernous, 500-cu-ft icebox where metal can be kept in cold storage. Larger than two box cars, the refrigerator deep-freezes metal plane parts to keep them soft—to hold their molecules in suspended animation—between two steps in fabrication. Main benefits from the manufacturing freeze treatment are easier shaping, reduced breakage, and smoother production flow.

Metallurgists explained the chill technique this way: Metal parts become soft (semihard) when they are subjected to high heat in a process which, in the end, gives them extra hardness and strength. If they are allowed to cool at normal room temperature they harden rapidly. Such hardness would be a hindrance during forming and shaping operations. But, it has been discovered, quick-freezing keeps the metals soft indefinitely. Parts heated to 970 F are quenched frozen, and then removed for forming while still cold and workable.

✦ ✦ ✦

ROY MARQUARDT, President of Marquardt Aircraft Company, recently broke ground to start construction work on a new engineering and office building. The two-story building is part of a $250,000 expansion program that includes

FIG. 10 G-E MT. WASHINGTON GAS TURBINE LABORATORY

modification and enlargement of the employees' cafeteria, paving and lighting of the employees' parking lot, installation of a plant-wide public address system, and new test laboratories.

Marquardt Aircraft is engaged in this expansion program of new and increased facilities to accommodate the increase of personnel and operations resulting from an all-time high backlog stated by Mr. Marquardt in his remarks at the ground-breaking event: "As of January 31, 1953, unfilled orders and contracts (exclusive of facilities contracts) aggregated approximately $14,000,000, for which funds of approximately $4,900,000 had been allocated by the Government, directly or indirectly."

The company is primarily a designer and manufacturer of power plants and accessories for pilotless aircraft and manned aircraft of advanced supersonic design; it is also engaged in long range research and development contracts for the Armed Forces.

✦ ✦ ✦

New Equipment

A NEW form of basic instrumentation for the precise measurement of gas pressures in the range between absolute vacuum and one atmosphere has been developed at the Navy Ordnance Laboratory. The new gage consists of two small beryllium-copper dish-shaped diaphragms which have been fastened to opposite sides of a ring to form a vacuum-tight chamber. Two sizes of this precision pressure gage are available at present. One is $^3/_4$ in. in diam and $^3/_8$ in. thick and can measure a change of pressure as low as 0.01 mm of mercury. The other gage is $^9/_{16}$ in. thick and can measure a change of pressure as low as 0.05 mm of mercury.

✦ ✦ ✦

DEVELOPMENT of the search and track radar, recently in the news for its work in detecting and shooting down a number of MIG's over Korea, stemmed from seven years of experiments with night-fighter radar equipment by Westinghouse Electric Corporation. This deadly radar equipment was manufactured for the Navy at their electronics plant in Baltimore. The equipment was developed under the supervision of the engineering staff members of the Air-Arm Division. They were stationed at the time at the company's Landsdowne plant while awaiting completion of the new Air-Arm plant which recently began production. The Division was organized in 1951 to handle development of such defense products as air-borne radar, guided missiles, and automatic pilots.

✦ ✦ ✦

AN EXCEPTIONALLY rugged thermocouple for meas-

uring transient temperatures is described by David Bendersky in the February 1953 issue of *Mechanical Engineering*. The couple, developed to measure bore temperatures in gun barrels, consists of an insulated internal lead wire inserted in a small metal tube. The end of the internal lead wire is made just flush with the end of the tube which is then closed by metal plating the tube end with the same metal as the internal lead wire. The plating metal, 1 micron thick, forms the thermal junction between the lead wire and the metal tube. A nickel-steel couple constructed in the manner described is reported to have a response time of less than 1 millisec.

✦ ✦ ✦

THE National Advisory Committee for Aeronautics, after independent research, has confirmed the invention of a valuable new optical instrument for aerodynamic research by Robert Kraushaar of the Research Division of New York University's College of Engineering. The special advantages of this instrument, known as a diffraction-grating interferometer, are its relatively low cost, easy adjustment, and large field of view. Kraushaar's invention may be used in many applications instead of the Mach-Zehnder interferometer, which is comparatively expensive because of the size, number, and accuracy required of the optical components and aligning mechanisms. The standard two-parabolic-mirror schlieren system can be converted inexpensively to a diffraction-grating interferometer, according to the NYU engineers.

Personalities

BARTON TYLER has been appointed executive assistant to J. GRANT MACDONNELL, administrative head of Northrop Aircraft's Special Weapons Division, it has been announced. A native of Cleveland, Ohio, Mr. Tyler first joined Northrop as an industrial engineer in May 1948. From 1950 to 1952 he was superintendent of production control at Piasecki Helicopter Co., Morton, Pa.

TWO civilian experts from the Navy Bureau of Aeronautics and the U. S. Air Force have joined the Ryan Aeronautical Company engineering department in key posts. They are G. A. ("Gabe") DANCH, for seven years with the Fighter Branch, Bureau of Aeronautics, and AL DEYARMOND, former chief of the special studies office, Air Technical Intelligence Center, Wright-Patterson Air Force Base, Dayton, Ohio. Danch will serve as executive assistant to BRUCE SMITH, Ryan director of Engineering, and will perform special assignments. Deyarmond actually is returning to Ryan, where he was chief of structures from December, 1946 to April, 1948, when he went to the Air Materiel Command's Intelligence Section. Deyarmond will again fill the reactivated post of chief of structures at Ryan and, in addition, will also be chief of aerodynamics.

✦ ✦ ✦

JOHN S. LIEFELD has been appointed factory manager of Marquardt Aircraft Company. Liefeld brings to Marquardt twenty years of experience in the automotive aircraft and metalworking fields. He has been associated with Chrysler Corporation, Consolidated Aircraft Corporation (now Convair), and Keller Motors Corporation of Alabama where he was an officer and director. Prior to joining Marquardt, he was with Aircraft Metal Forming Company of Burbank, Calif.

✦ ✦ ✦

LYSLE A. WOOD, Boeing Airplane Company chief engineer since 1948, has been appointed to the newly created post of Director of Pilotless Aircraft.

✦ ✦ ✦

GEORGE D. CREMER (Assoc. Member ARS), research engineer at Solar Aircraft Company, San Diego, presided at a panel session during the annual meeting of the American Institute of Mining and Metallurgical Engineers. Mr. George Stern (Member ARS) of American Electro Metals was a member of the panel.

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American Rocket Society News

H. K. WILGUS, *Associate Editor*

Two Technical Sessions Scheduled for ARS Summer Meeting at Los Angeles, Calif., July 2, 1953

THE American Rocket Society is planning two technical sessions at its Summer Meeting on July 2, 1953, at the Hotel Statler, Los Angeles, Calif., to be held in conjunction with the ASME Semi-Annual Meeting, June 28–July 2.

The tentative program follows:

Morning Session, 9:30 a.m.

Chairman: R. D. Geckler, Aerojet Engineering Corporation, Azusa, Calif.

Vice-Chairman: Leon Green, Jr., Aerojet Engineering Corporation, Azusa, Calif.

Correlation of Experimental Data on the Disintegration of Liquid Jets, by C. C. Miesse, Aerojet Engineering Corporation, Azusa, Calif.

Rocket-Powered Wind Tunnel, by F. Kreith, P. Stewart, and E. Starkman, University of California, Berkeley, Calif.

A third paper yet to be selected will be presented at this session.

Luncheon Meeting, 12:30 p.m.

Chairman: B. L. Dorman, Aerojet Engineering Corporation, Azusa, Calif.

Speaker: C. E. Yeager, Experimental Flight Test Center, Edwards Air Force Base, Calif.

Subject: Experiences in Rocket-Propelled Aircraft.

Afternoon Session, 2:30 p.m.

Chairman: S. K. Hoffman, North American Aviation, Inc., Aerophysics Laboratory, Downey, Calif.

Vice-Chairman: L. E. Stocking, Douglas Aircraft Corporation, Santa Monica, Calif.

Air Transportable 10-Ton-Per-Day Liquid Oxygen Generator, by C. L. Jewett, Arthur D. Little, Inc., Cambridge, Mass.

Solid Propellant Rockets—Basic Concepts, Present Status, and Trends in Development, by C. E. Bartley, Grand Central Aircraft Company, Pacoima, Calif.

A third paper yet to be selected will be presented at this session.

Southern California Section Elects Officers for 1953

AT A MEETING of the Southern California Section on February 25, 1953, the following officers were elected to hold office for the year 1953.

President, S. K. Hoffman, North American Aviation, Inc., Aerophysics Laboratory, Downey, Calif.; *Vice-President,* H. S. Seifert, Jet Propulsion Laboratory, CalTech, Pasadena, Calif.; *Secretary-Treasurer,* R. D. Geckler, Aerojet Engineering Corporation, Azusa, Calif.; *Board of Directors,* B. L. Dorman, Aerojet Engineering Corporation; D. I. Baker, Jet Propulsion Laboratory, CalTech; E. G. Crofut, Aerolab Development Company, Pasadena, Calif.; W. D. Crossland, North American Aviation, Inc., Field Test Laboratory, Santa Susanna, Calif.; C. M. McCloskey, Office of Naval Research, Pasadena, Calif.; and L. E. Stocking, Douglas Aircraft Corporation, Santa Monica, Calif.

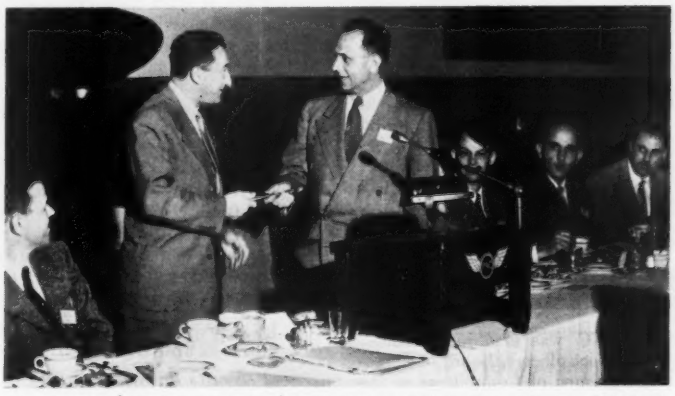
Two Papers Presented at Meeting

Following the election of officers, the members and guests heard papers given by Chester G. Hylkema and Irving L. Odgers, both of the Jet Propulsion Laboratory, California Institute of Technology.

Mr. Hylkema's subject was "The Interpretation of the Transient Response of Pressure Gages." Combustion instability phenomena, he stated, have focused attention on the performance characteristics and limitations of pressure measuring systems. For faithful reproduction of pressures, the measuring system must be characterized by linearity, a flat amplitude response over the frequency range, and a phase shift proportional to frequency. Whereas these characteristics of most electrical circuits can easily be determined by oscillatory forcing functions, he said, only nonperiodic forcing functions are available for test with pressure measuring systems, particularly for the pressures incident with motor operations. Fourier integral relationships uniquely relate time functions and frequency functions. Therefore, Mr. Hylkema pointed out, it is possible to determine the amplitude-phase transfer characteristics from the nonperiodic data obtained from tests on gages. The large amount of computation necessary is feasible with the advent of high-speed digital computers. The examination of the characteristics of various commonly used pressure gages, the speaker concluded, indicates the necessity for considerable improvement.

Mr. Odgers spoke on "Experimental Investigation of Combustion Instabilities in Rocket Motors." He pointed out that the large chamber pressure oscillations frequently observed in rocket motors are often of sufficient amplitude to cause damage to the rocket motor. Though some experimental work has been done, he said, the difficulties encountered with instrumentation have prevented obtaining a good experimental description of the combustion instability phenomena necessary to confirm or deny existing theories. Preliminary work in the instability program at the Jet Propulsion Laboratory has been concentrated on obtaining an accurate description of the different types of instability.

Simultaneous pressure measurements along tubular rocket motors, the speaker stated, has indicated two dominant types of axial oscillations. One type seems associated with the feed system, injector, and propellant combination because the frequency of this type does not vary markedly with chamber length. The other



B. L. DORMAN (SECOND FROM LEFT), RETIRING PRESIDENT, SOUTHERN CALIFORNIA SECTION, RELINQUISHES HIS GAVEL TO THE NEW PRESIDENT, SAMUEL K. HOFFMAN OF NORTH AMERICAN AVIATION, INC., AT THE MEETING ON FEBRUARY 25, 1953

(Seated, left to right): H. S. Seifert, Jet Propulsion Laboratory, CalTech, vice-president; Irving L. Odgers, Jet Propulsion Laboratory, guest speaker; and two members of the Section's Board of Directors, D. I. Baker, Jet Propulsion Laboratory, and E. G. Crofut, Aerolab Development Company.

type, he said, seems to be associated with the length of the chamber because the frequency of this type varies approximately inversely with the chamber length.

Indications are, Mr. Odgers concluded, that by using the technique of simultaneous measurements of related phenomena, sufficient information can be gathered to give much better pictures of combustion instability phenomena.

March Dinner Meeting

Members and guests who attended the Southern California Section Dinner Meeting on March 26, 1953, at the Institute of the Aeronautical Sciences Building, Los Angeles, Calif., heard two guest speakers, David Narver, of the engineering firm of Holmes and Narver, and Dr. Stafford L. Warren, dean of the University of California at Los Angeles Medical School.

Mr. Narver, who had designed and built most of the physical facilities for the Bikini atom-bomb tests, showed a spectacular film dealing with those tests. It was in color, and illustrated the care and precision required in setting up such tests, and gave a graphic picture of the beauty and violence of atomic detonations.

Dr. Warren's paper was on the subject of radiation medicine. It dealt with the instantaneous deaths due to heat and blast, and the delayed, quiet, lazy death of radiation sickness. The speaker outlined some of the unknowns connected with the after-effects of atomic explosions: What are the reasons that some are killed and others not? What are the physical causes of death by concussion? What are the limits on daily doses of radiation without lethal effects, and how long will the effects of radiation on populations continue to be felt? What are lethal pressure limits in man? What is the best protection?

Dr. Warren stated that 200 or so bombs dropped anywhere in the western part of the United States could cause the country to become uninhabitable because of contamination of food-producing areas and deposition of radiation products by wind and precipitation. Bone-building grains, he said, such as our daily cereal, take up the radiation from the ground over which the radioactive cloud has passed. This may be several hundred square miles in area, and the grains are radioactive year after year. They apparently do not affect meat and muscle, but do attack bone marrow and the liver and cause eventual death. Dr. Warren stated that it would be possible to decontaminate food-producing ground by growing alfalfa to feed beef and cattle, and by rigid segregation of all bones, liver, and manure. The meat apparently could be used without harm.

New Mexico-West Texas Section Elects 1953 Officers

A MEETING was held in December 1952 to elect officers, Board of Directors, and chairmen of Committees of the ARS New Mexico-West Texas Section for the calendar year 1953.

The following officers were chosen: *President,* Edward E. Francisco, Jr.; *Vice-President,* Lawrence W. Gardenhire; *Secretary-Treasurer,* Frank L. Koen, Jr.

The new Board of Directors consists of: R. B. Bolles, Lt. Col. M. R. Collins, Brig. Gen. G. G. Eddy, F. A. Koether, G. L. Meredith, L. D. White, and C. W. Tombaugh.

Mr. Meredith was appointed Chairman of the Membership Committee; Ray Minichiello, Chairman of the Program Committee; and H. S. Stine, Chairman of the Publicity Committee.

(Photograph courtesy of White Sands Proving Ground)

DR. R. W. PORTER PRESENTING TO BRIG. GEN. G. G. EDDY, COMMANDING GENERAL, WSPG, A PAINTING BY PETER HURD PORTRAYING A TEST MISSILE RISING FROM THE LAUNCHING SITE OF WSPG AGAINST A BACKGROUND OF THE ORGAN MTS

Major Simons at January Meeting

At the first meeting of the year, January 29, 1953, the New Mexico-West Texas Section had as its guest speaker, Major D. G. Simons of the Space Biology Laboratory, Holloman Missile Test Center.

The subject of Major Simons' address was "Space Biology." The effects of no-gravity, or "zero-g," pose no problems to living organisms, he stated. The recent high-altitude rocket flights carrying monkeys and white mice disclosed no ill effects due to zero-g. Loss of orientation, he said, appears to be the major difficulty of weightlessness. Showing motion pictures taken of white mice in zero-g, Major Simons pointed out that no loss of orientation was experienced by the mouse which had something to hold on to.

Monkeys have also been sent aloft, and the effects of cosmic radiation and acceleration have been studied. The speaker said that cosmic radiation effects have been overstressed, that the total exposure on short rocket flights was less than that received from a standard x-ray machine. Human beings, he added, could withstand a prolonged, six months' exposure to the cosmic radiation that would be experienced on an artificial satellite.

R. W. Porter Discusses Use of Rockets and Guided Missiles

Presents Painting to WSPG

On March 2, 1953, the Section was privileged to have as guest speaker R. W. Porter, General Manager of the Guided Missile Division, General Electric Company, and member of the ARS Board of Directors. Speaking on "The Use of Rockets and Guided Missiles," he pointed out that although conventional aircraft have definite advantages with respect to payload-vs.-airframe weight up to intercontinental ranges, the rocket shows definite promise of being successful at both tactical and strategic ranges.

Stressing the problems encountered by rocket design engineers, the speaker took as an example a theoretical missile with a range of 100 miles. He discussed problems of burning time, aerodynamic configuration, mixture ratio, mass ratio, and specific impulse of this fictional missile, pointing out several engineering short cuts.

A high light of the meeting was the presentation by Dr. Porter to Brig. Gen. G. G. Eddy, Commanding General, White Sands Proving Ground, of a painting by the nationally known New Mexico artist, Peter Hurd. The painting, which portrays a guided missile making its vertical ascent against a background of the Organ Mountains, was presented to WSPG by the General Electric Company as a token of deep respect for General Eddy and the post he commands.

IAF Fourth Congress at Zurich, August 3–8

THE Fourth Congress of the International Astronautical Federation will be held at Zurich, Switzerland, during the week of August 3–8, 1953. The Schweizerische Astronautische Arbeitsgemeinshaft at Baden will act as host to the member societies. Dr. Josef A. Stemmer, Secretary of the IAF, is President of the Swiss Society.

As previously at Stuttgart, London, and Paris, delegates of professional rocket and "space travel" societies from Great Britain, Norway, Sweden, Denmark, Holland, France, Germany, Austria, Italy, Spain, Switzerland, Argentina, and the United States will attend. The American Rocket Society is the voting member for the United States.

Following the business sessions which will deal with new members, standardiza-

tion of nomenclatures, and other matters, several days of technical sessions will be held. At these sessions, scientific and technical papers will be presented on the problems of achievement of space flight and the artificial satellite. Dr. Eugen Saenger, IAF President, will preside.

At this writing, an official program for the technical sessions of the Congress has not yet been compiled, however, such a program will be attainable from the New York office of the American Rocket Society at a later date.

ARS Members who may be able to attend the Congress are requested to write to ARS Vice-President Andrew G. Haley (Vice-President IAF), 1101 Connecticut Ave., Washington, D. C., in order that their names may be included in the list of official ARS delegates.

New ARS Cleveland-Akron Section is Formed

THE latest group to join the American Rocket Society is the newly formed Cleveland-Akron Section which held its organizational meeting on March 26, 1953, at the Case Institute of Technology, Cleveland, Ohio.

The guest speaker was Benjamin Pinkel, Chief, Materials and Thermodynamics Division, NACA Lewis Flight Propulsion Laboratory, Cleveland, Ohio. Mr. Pinkel spoke on the application of nuclear energy to various propulsion devices for aircraft, including the rocket.

The business meeting, held after Mr. Pinkel's lecture, was devoted to an acceptance of originally submitted By-Laws, and the election of the following officers: *President*, Darrell C. Romick, Goodyear Aircraft, Akron, Ohio; *Vice-President*, John L. Sloop, NACA; *Sectary-Treasurer*, R. E. Knight, Goodyear Aircraft; *Directors* (*2-year*), Prof. H. Burlage, Case Institute of Technology, and (*1-year*), W. T. Olson, NACA.

The following committees were also set up: Program Committee, J. L. Sloop, *Chairman;* Membership Committee, H. Burlage, *Chairman;* Publicity Committee, T. B. Woersching, of Goodyear Aircraft, *chairman;* Transportation Committee, Howard Douglass of NACA, *Chairman;* Finance and Budget Committee, R. E. Knight, *Chairman.*

Golay Addresses Northeastern New York Section

APPROXIMATELY 75 members and guests attended the Northeastern New York Section Meeting held in the General Engineering Building at Union College, Schenectady, N.Y., on April 14, 1953. The guest speaker for the evening was Marcel J. E. Golay, chief scientist, Squier Laboratory, Army Signal Corps.

Dr. Golay, who spoke on "Interplanetary Rocket Guidance," illustrated the type of path which would be followed in a journey to Mars. He described the type of radio interferometry equipment which would be required, and indicated the degree of accuracy necessary for completing the mission successfully.

Alabama Section Announces 1953 Officers

AT A MEETING held in March 1953, the ARS Alabama Section held an election at which the following Board of Directors was chosen: *3-year terms*: Wernher von Braun, H. W. Ritchey, and Martin Schilling; *2-year terms*: James L. Stamy, Hans Hueter, and George Henderson; *1-year term*: John Dawson, Adolph K. Thiel, and E. Stuhlinger.

The new Board of Directors then elected the following officers for 1953: *President*, George Henderson, engineering consultant; *Vice-President*, John Dawson, Chief, Research Division, Redstone Arsenal; *Secretary*, James L. Stamy, Launching and Handling Equipment Laboratory.

RETIRING AND RECENTLY ELECTED OFFICERS OF THE ALABAMA SECTION AT THE SECTION MEETING IN MARCH, 1953

(*Front row, left to right):* George Henderson, engineering consultant, the new president; Martin B. Schilling, deputy chief, Technical and Engineering Division, Redstone Arsenal, the retiring president.

(*Standing, left to right):* James L. Stamy, Launching and Handling Equipment Laboratory, Redstone Arsenal, re-elected secretary; John Dawson, chief, Research Division, new vice-president; and Hans Hueter, chief, Launching and Handling Equipment Laboratory, retiring vice-president.

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Book Reviews

H. S. SEIFERT, California Institute of Technology, *Associate Editor*

INSTRUMENT ENGINEERING, VOL. I, FUNDAMENTALS: METHODS FOR DESCRIBING THE SITUATIONS OF INSTRUMENT ENGINEERING, by C. S. Draper, W. McKay, and S. Lees, McGraw-Hill Book Co., Inc., New York, N. Y., 1952. $6.

Reviewed by CHESTER HYLKEMA
California Institute of Technology
Jet Propulsion Laboratory

The authors define instrument engineering as "the art and science by which the properties of matter and the laws of nature are made useful to man in the observation and control of physical processes." The breadth of the subject is reflected in the material surveyed in the book. A partial list of the topics includes functional and mathematical diagrams, static and dynamic performance, dimensional analysis, derivation of performance equations, statistical methods, Fourier transformation, time series, plane-wave phenomena, and sinusoidal-response characteristics. A chapter on the applications of statistical methods, by H. B. Brainerd, is included.

This book is one of three volumes. Contrary to the usual organization of a technical series in which complete treatments of the respective subjects are presented successively, the subjects are presented in parallel. This volume presents the fundamentals of the topics stated in the first paragraph, which will be further developed in Vol. II, with examples given in Vol. III. Obviously Vol. I is of particular value as background for Vol. II and is probably indispensable to it. The review of a single volume of this series is therefore somewhat inadequate, as would be the review of scattered portions of a single-volume work. The theoretical fundamentals of instrumentation are derived from many sources: physics, mathematics, and many of the engineering fields. This fact is conducive to diversity and confusion in the nomenclature. It is the objective of Volume I to unify the subjects gathered from these diverse sources by defining concepts and notation appropriate to instrument engineering. The treatment assumes a basic familiarity with the subjects mentioned in the first paragraph, and for readers not so equipped a helpful bibliography is given. Anyone attempting to make casual reference to the book will probably be overwhelmed by the variety and complexity of the symbols. An appreciation and understanding of this notation require fairly intensive study of the book.

The text gives evidence of detailed knowledge born of the authors' years of experience. The book is recommended for engineers interested in the details of instruments and control systems, their design and development, manufacture, performance, and analysis.

DESIGN AND ANALYSIS OF EXPERIMENTS, by O. Kempthorne, John Wiley & Sons, Inc., New York, N. Y., 1952, 631 pp. $8.50.

EXPERIMENTAL DESIGNS, by W. G. Cochran and G. M. Cox, John Wiley & Sons, Inc., New York, N. Y., 1950, 454 pp. $5.75.

Reviewed by C. R. GATES
California Institute of Technology
Jet Propulsion Laboratory

Physical experiments and their associated instrumentation are intimately linked with the inductive processes of reasoning which lead from measured data to the confirmation of a proposed hypothesis or the estimation of a parameter. Statistics has been recognized as a useful tool in the analysis of experimental observations, but important results of the last 30 years indicate that incorporating the statistical theory into the experiment at the earliest possible stage produces the greatest degree of confidence in the final decision.

These two books treat the problem of designing experiments which will yield the best results from the smallest number of observations. The books are complementary: Kempthorne presents a theoretical basis for the statistically efficient planning of experiments, and Cochran and Cox describe in detail useful designs, with an account of situations for which each design is most suitable. Together the two books contain most of known statistics that is likely to be useful to the experimenter, including least-squares techniques, the analysis of variance, randomization, and confounding, and the use of randomized blocks. Double and sequential sampling are notable exceptions.

Both of these books require a prior knowledge of elementary statistics, and the novice is advised first to consult a text such as "Introduction to Mathematical Statistics" by P. G. Hoel (Wiley, New York, 1947), or "Introduction to the Theory of Statistics," by A. M. Mood (McGraw-Hill, New York, 1950).

SELECTED TOPICS IN MODERN INSTRUMENTAL ANALYSIS, by D. F. Boltz et al., Prentice-Hall, Inc., New York, N. Y., 1952, 477 pp. $8.

Reviewed by K. N. TRUEBLOOD
University of California at Los Angeles

This book was prepared as a text for a course offered to seniors and first-year graduate students in chemistry. Ten specialists have contributed to the ten chapters, which deal with electrometric pH measurements, polarography, fluorometry, spectrophotometry, spectrochemical analysis, miscellaneous electrical and optical methods, analytical applications of x-ray diffraction, mass spectrometry, Raman spectroscopy, and radiochemical analysis.

The editor has achieved a degree of uniformity of approach in that each chapter presents an organized discussion of principles, characteristics of typical instruments, and applications. However, the chapters vary in length from 16 pages (radiochemical analysis) to 76 pages (x rays), and it appears to the reviewer that the considerable variation in conciseness of writing and scope of treatment is more casual than planned and does not reflect the relative importance of the various techniques.

The discussions are throughout generally clear, logical, and timely. A very commendable effort is made to emphasize repeatedly the most significant factors in each method and to summarize the advantages and disadvantages of various alternate techniques. However, these desirable features are offset in part by several omissions which detract from the utility of the book. Only two of the chapters have adequate introductions or summaries which give any real hint of their content or scope. The index helps here only partially; indeed, the index seems only barely adequate for a book of this sort, which may be used as a reference. Furthermore, although valuable literature references are collected at the end of each chapter, citations of them in the text are often spotty; three of the chapters contain no citations to their own listed references, a situation alleviated only in part by the presentation of complete titles of some of the papers listed.

In summary the book represents a reasonably lucid and authoritative introduction to the topics mentioned, adequate for one wishing a general survey but less desirable for the research worker, especially if he has access to the far more comprehensive and critical compendia, such as Weissberger's "Technique of Organic Chemistry" series, or Berl's "Physical Methods in Chemical Analysis."

LABORATORY INSTRUMENTS, THEIR DESIGN AND APPLICATION, by A. Elliott and J. Home Dickson, Chapman and Hall, Ltd., London, 414 pp. $6.50 (American edition).

Reviewed by MERVIN E. FRANK
California Institute of Technology
Jet Propulsion Laboratory

This book is intended for research workers who construct their own instruments or who guide others in problems of construction. In subject matter, it is roughly comparable to Strong's "Procedures in Experimental Physics." There are almost no descriptions of complete instruments except a few optical instruments. Rather, mechanisms and materials used in building instruments are discussed.

There are several chapters on materials (woods, metals, plastics, and glass) and on treatment of these materials (e.g., casting, welding, and heat treating). The chapters on drawing and machine-shop practice emphasize the setting of reasonable tolerances and state the accuracies to be expected in various machining operations. Supplementing these chapters is a chapter giving special tests for straightness, flatness, and squareness.

The "kinematic design" of instruments is discussed at some length. There is one chapter each on vibration isolation, sensitivity, and damping.

About half the book is devoted to optics and optical instruments. The chapter on glass working is concerned with operations such as grinding, drilling, and polishing which are used in lens making; no mention is made of glass blowing.

The section of lenses contains numerous tables and diagrams showing the characteristics and construction of specific lenses. The lenses are listed under their commercial names; e.g., under camera lenses are such names as Tessar, Ektar, and Zoomar. Listed in this fashion are eyepieces, magnifiers, telescope objectives, microscope objectives, camera lenses, condensers, and prisms. Various optical systems are described. There is a chapter on photography.

At the end of each chapter, references are given which provide further information on the subjects covered. Many of the standards and trade names mentioned in this book are British and may not be familiar to an American reader. The title might better describe the contents if the word "optical" were inserted. There is no mention of instruments for taking such measurements as temperature or pressure, and chemical and electrical instruments are largely ignored. Throughout the book, strong emphasis is placed on the necessity for setting realistic tolerances, and on designing to ease the requirements for materials and workmanship.

THE MEASUREMENT OF AIR FLOW, by E. Owens, 3rd Edition, Chapman and Hall, Ltd., London, 1949, 293 pp. 30*s*.

Reviewed by R. J. BERG
California Institute of Technology
Jet Propulsion Laboratory

Most of the methods commonly used by engineers for the measurement of air flow are discussed in this book. Chapters are included on air-flow measurement by Pitot tubes, orifice plates, Venturis, the vane anemometer, and other less widely used methods.

The first three chapters are particularly valuable to beginners in the field. In these chapters Reynolds number, Bernoulli's equation, and elementary boundary-layer theory are discussed.

The next five chapters are devoted to particular flow-measurement methods, the practical approach being emphasized throughout. These chapters discuss the most widely used applications of a particular method, the commercial equipment available, and the probable error to be expected. Sufficient theory is included for an adequate understanding of the problem. Of special value to the occasional users of equipment for measuring air flow are sketches showing standard dimensions for use in constructing Pitot tubes, Venturis, and orifice plates. Numerous practical hints for their design and installation are included.

The author has wisely included a chapter on the manometer with special emphasis on manometers suitable for use with low differential pressures. This chapter is especially appropriate in view of the wide use of manometers in air-flow measurement. A chapter on flow-measurement methods based upon the rate of cooling of a hot body, and a final chapter containing examples from practice complete the text.

A BIBLIOGRAPHICAL SURVEY OF FLOW THROUGH ORIFICES AND PARALLEL THROATED NOZZLES, T. H. Redding, Chapman and Hall, Ltd., London, 196 pp. 32*s* 6*d*.

Reviewed by R. J. BERG
California Institute of Technology
Jet Propulsion Laboratory

Over 600 references are included in this bibliography on the flow of both liquids and gases through orifices and parallel-throated nozzles. These references are grouped under sixteen subject headings, so that the location of a reference on any particular subject is relatively easy. A concise, one- or two-sentence description of the material covered is included with each reference.

In addition to the bibliography itself, there is an appendix which gives English translations of all titles in foreign languages. A second appendix lists the 240 periodicals from which the bibliography was compiled. A third appendix provides definitions for many of the technical terms used.

METHODS OF APPLIED MATHEMATICS, by F. B. Hildebrand, Prentice-Hall, Inc., New York, N. Y., 1952, 523 pp. $7.75.

Reviewed by MORGAN WARD
California Institute of Technology

This book gives a clear account of some of the more advanced mathematical methods used in current engineering research. The material present is basically a selection from, and condensation of, the classical *Methoden der Mathematischen Physik* of Courant and Hilbert which has proved so useful to theoretical physicists for the past 20 or 30 years.

Topics treated center around linear algebra, calculus of variation, difference equations, and integral equations. The book is written as a text, but numerous problems with answers should enhance its value for self-study.

ELASTICITY IN ENGINEERING, by E. E. Sechler, John Wiley & Sons, New York, N. Y., 1952, 419 pp. $8.50.

Reviewed by G. HOUSNER
California Institute of Technology

This book, the latest addition to the GALCIT Aeronautical Series, deals with the theory of elasticity and advanced strength of materials. The contents are divided into three parts. The first 120 pages present the fundamentals of the theory of elasticity, covering stresses and strains, basic equations, stress function, and elastic energy principles. The second part deals with applications to two-dimensional stress problems, beams, continuous and redundant structures, torsion, plates, and shells. The third part of the book is devoted to instability problems, namely, buckling of columns and beams, and the instability of plates and shells.

The contents of the book have clearly been selected with practical applications in mind; all of the methods and problems discussed are of the type often encountered by engineers, particularly aeronautical engineers. The material is presented with detail and clarity so that it is well suited for postcollege reading.

Recent Books on Various Aspects of Jet Propulsion

Automatic and Manual Control, collection of papers by W. E. Scott, N. Minorsky et al., Academic Press Publications, N. Y., 1952, 318 pp. $10.

Electric Resistance Strain Gauges, by W. B. Dobie and P. C. G. Isaac, The Macmillan Co., N. Y., 1949, 114 pp., 90 illus. $4.

Techniques of Magnetic Recording, by J. Tall, The Macmillan Co., N. Y., 1952, 400 pp., illus. $4.50.

Instrument Electronics, by M. H. Aronson, The Instrument Publishing Co., 921 Ridge Ave., Pittsburgh 12, Pa. (in preparation).

Mechanics of Vibration, by H. M. Hansen and P. F. Chenea, John Wiley & Sons, Inc., N. Y., 1952, 417 pp., illus. $8.

Weight-Strength Analysis of Aircraft Structures, by F. R. Shanley, McGraw-Hill Book Co., Inc., N. Y., 1952, 406 pp., 187 illus. $8.50.

Papers of the 1952 Heat Transfer and Fluid Mechanics Institute, Stanford University Press. Stanford, Calif., 186 pp. $4.

Supersonic Aerodynamics, by E. R. C. Miles, McGraw-Hill Book Co., Inc., N. Y., 1952, 255 pp., 106 illus. $4.50.

The Mathematical Theory of Non-Uniform Gases, by S. Chapman and T. G. Cowling, The Macmillan Co., N. Y., 1952, 431 pp. $7.50.

Descriptive Meteorology, by H. C. Willett, Academic Press Publications, N. Y., 1952, 310 pp. $6.

Cosmology, by H. Bondi, Cambridge University Press, N. Y., 1952. $4.50.

Advances in Applied Mechanics, Vol. II, by T. von Kármán and R. von Mises (editors), Academic Press Publications, N. Y., 1951, 233 pp. $6.50.

Advances in Applied Mechanics, Vol. III, by T. von Kármán and R. von Mises (editors), Academic Press Publications, N. Y., 1953 (in preparation).

Advances in Electronics, Vol. IV, by L. Marton (editor), Academic Press Publications, N. Y., 1952, 344 pp. $7.80.

Imperfections in Nearly Perfect Crystals, by W. Shockley et al., John Wiley & Sons, Inc., N. Y., 1952, 490 pp., 162 illus. $7.50.

Refractory Hard Metals, by P. Schwarzkopf and R. Kieffer, The Macmillan Co., N. Y., 1952, 400 pp., 92 illus. $7.50.

Technical Literature Digest

M. H. SMITH and M. H. FISHER

The James Forrestal Research Center, Princeton University, Princeton, N. J.

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An Energy Basis for Comparison of Performance of Combustion Chambers, by J. B. Nichols, *Trans. ASME*, vol. 75, Jan. 1953, pp. 29–34.

Temperature Control of Jet-Engined Aircraft, by E. W. Still, *J. Roy. Aero. Soc.*, vol. 57, Feb. 1953, pp. 89–102.

Turbo Jet Power Control Trends, by C. S. Constantino, *SAE Preprint* no. 820, Oct. 1952, 5 pp., 2 figs.

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British Turbojets, by C. S. Constantino, *SAE J.*, vol. 61, Jan. 1953, p. 55.

The Application of the Ramjet to Aircraft Propulsion, by M. Harned, ASME Ann. Meet., Dec. 1952, 13 pp., 15 figs.

Experimental Investigation of Loss in an Annular Cascade of Turbine-Nozzle Blades of Free Vortex, by M. G. Kobsky and R. E. Chamness, *NACA TN* no. 2871, Jan. 1953, 33 pp.

Performance Calculations for a Double-Compound Turbo-Jet Engine of 12:1 Design Compressor Pressure Ratio, by D. H. Mallinson and W. G. E. Lewis, *Great Britain, Aero. Res. Counc. R & M* no. 2645 (formerly *ARC Tech. Rept.* 11,355; *National Gas Turbine Establ. Rep.* R19), 1952, 29 pp., 16 figs.

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Method of Analysis for Compressible Flow Through Mixed-Flow Centrifugal Impellers of Arbitrary Design, by Joseph T. Hamrick, Ambrose Ginsburg, and Walter M. Osborn, *NACA Rep.* no. 1082 (formerly *TN* no. 2165), 1952, 10 pp.

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Boundary-layer Stability and Transition in Subsonic and Supersonic Flow, by Carl Gazley, Jr., *J. Aero. Sci.*, vol. 20, Jan. 1953, p. 19.

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Combined Effect of Damping Screens and Stream Convergence on Turbulence, by Maurice Tucker, *NACA TN* no. 2878, Jan. 1953, 62 pp.

Factors Affecting the Performance of Supersonic Diffusers, by A. M. Patterson, *Toronto Univ., Inst. Aerophysics, UTIA Rep.* no. 23, Dec. 1952, 22 pp., 5 tabs., 26 figs.

On the Stability of the Laminar Mixing Region Between Two Parallel Streams in a Gas, by Chia-Chiao Lin, *NACA TN* 2887, Jan. 1953, 50 pp.

EDITOR'S NOTE: This collection of references is not intended to be comprehensive, but is rather a selection of the most significant and stimulating papers which have come to the attention of the contributors. The readers will understand that a considerable body of literature is unavailable because of security restrictions. We invite contributions to this department of references which have not come to our attention, as well as comment on how the department may better serve its function of providing leads to the jet propulsion applications of many diverse fields of knowledge.

Combustion

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A Study of Burner Oscillations of the Organ-pipe Type, by A. A. Putnam and W. R. Dennis, *Trans. ASME*, vol. 75, Jan. 1953, pp. 15–28.

Water Channel Analog to High Velocity Combustion, by A. K. Oppenheim, *ASME Paper* no. 52—A-3, 1953, 7 pp.

The Effect of Combustion Time on Knock in a Spark Ignition Engine, by D. R. Diggs, *SAE Preprint* no. 19, Jan. 1953, 10 pp.

Studies on the Spontaneous Ignition of Fuels Injected Into a Hot Air Stream. Part VI. Ignition Delay Measurement on Organic Compounds Containing Nitrogen or Halogen, by B. P. Mullins, *Great Britain National Gas Turbine Establ. Rep.* no. 106, July 1952, 20 pp., 37 tabs., 16 figs.

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A Small Combustion Chamber for Flame Temperature Measurements Under Reduced Pressure, by V. E. Henry, *Fuel*, vol. 32, Jan. 1953, pp. 36–38.

The Theory of Flame Propagation. IV, by J. O. Hirschfelder, C. F. Curtiss, and Dorothy E. Campbell, *Wisconsin Univ. Naval Res. Lab.*, CM 756, Nov. 1952, 48 pp.

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The Upper Limit of Inflammability of Hydrogen-air and Hydrogen-nitrous Oxide Mixtures, by S. Smith, and J. W. Linnett, *J. Chem. Soc.*, Jan. 1953, pp. 37–43.

Flame Velocities in Carbon Monoxide-oxygen Mixtures, by T. W. Price and J. H. Potte, *Trans. ASME*, vol. 75, Jan. 1953, pp. 91–96.

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The Thermodynamics of Combustion: Temperatures of Methane-air and Propane air Flames at Atmospheric Pressure, by R. W. Smith, Jr., H. E. Edwards, and Stuart Brinkley, Jr., *Bureau of Mines Rep. of Investigations* no. 4938, Jan. 1952, 3 pp.

Basic Flame Studies and Their Relationship to Welding Equipment, by James A. Browning and Merle L. Thorpe, *Project SQUID, Tech. Mem.* DART-3 (reprinted from *Welding J., Res. Suppl.*, Oct. 1952), 4 pp.

Combustion in the Gas Turbine. A Survey of War-Time Research and De-

Applications of cathode-ray oscillography

DISPLACEMENT vs. PRESSURE

The Physical Setup: A pressure-relief (poppet) valve fed by high-pressure air or gas.

The Problem: To determine motion of the valve in relieving excessive pressure and to record pressure during valve operation. Maximum linear valve motion is only 0.040".

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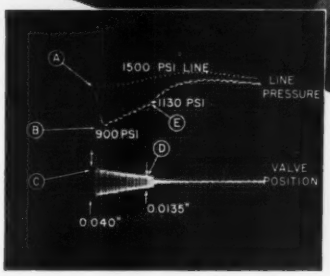
To measure valve displacement, a differential-transformer armature is attached to the valve shaft. Signal from an audio oscillator is applied to the transformer. Valve motion displaces the armature and a signal appears at the transformer secondary directly proportional to valve displacement. This signal, applied to the second channel of the oscillograph, triggers the sweep when the valve is opened.

Static measurements were used to calibrate the oscillograph. The oscillogram, recorded by an oscillograph record camera**, shows that the pressure drops rapidly from 1500 psi (A) to 900 psi (B) in about 0.027 seconds when



the valve "pops" to relieve pressure. The valve begins to close linearly from its maximum travel of 0.040 inches (C) until it is 0.0135 inches (D) from closed where it suddenly "pops" closed and is inoperative until the pressure again reaches 1500 psi. During valve closure, pressure builds up slowly from 900 psi (B) to 1130 psi (E) where the valve "pops" closed and then more rapidly approaches the static 1500 psi line along a logarithmic path determined by damping of the line and valve at the pressure source.

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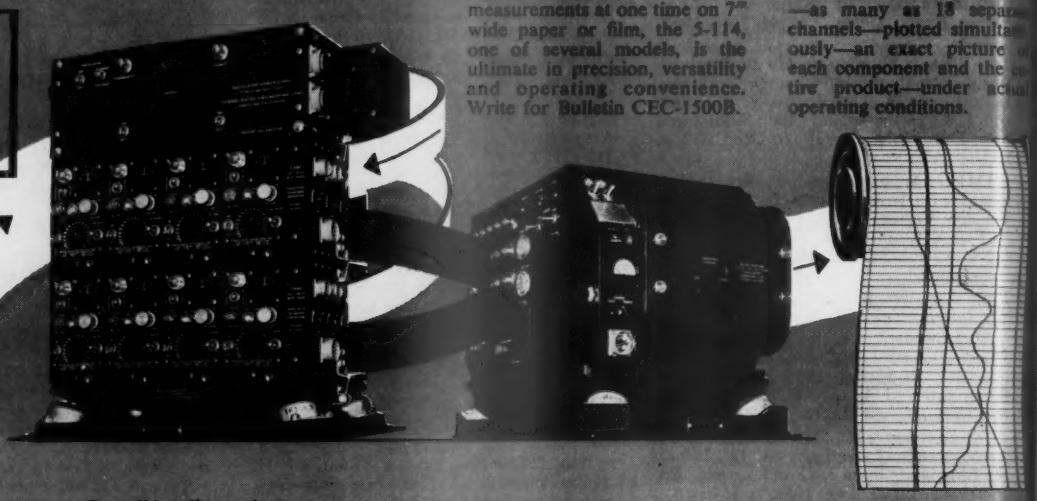

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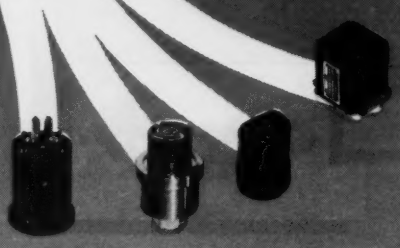

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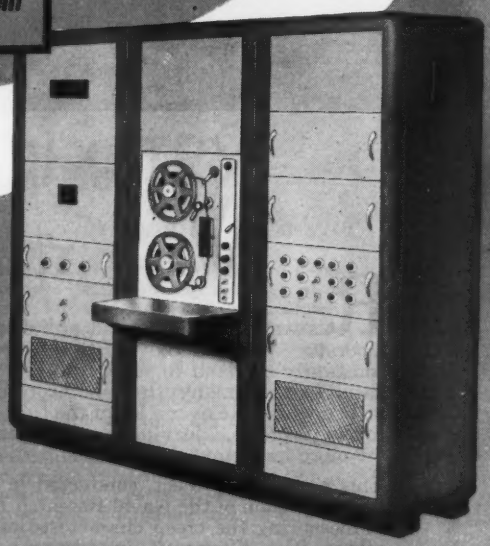

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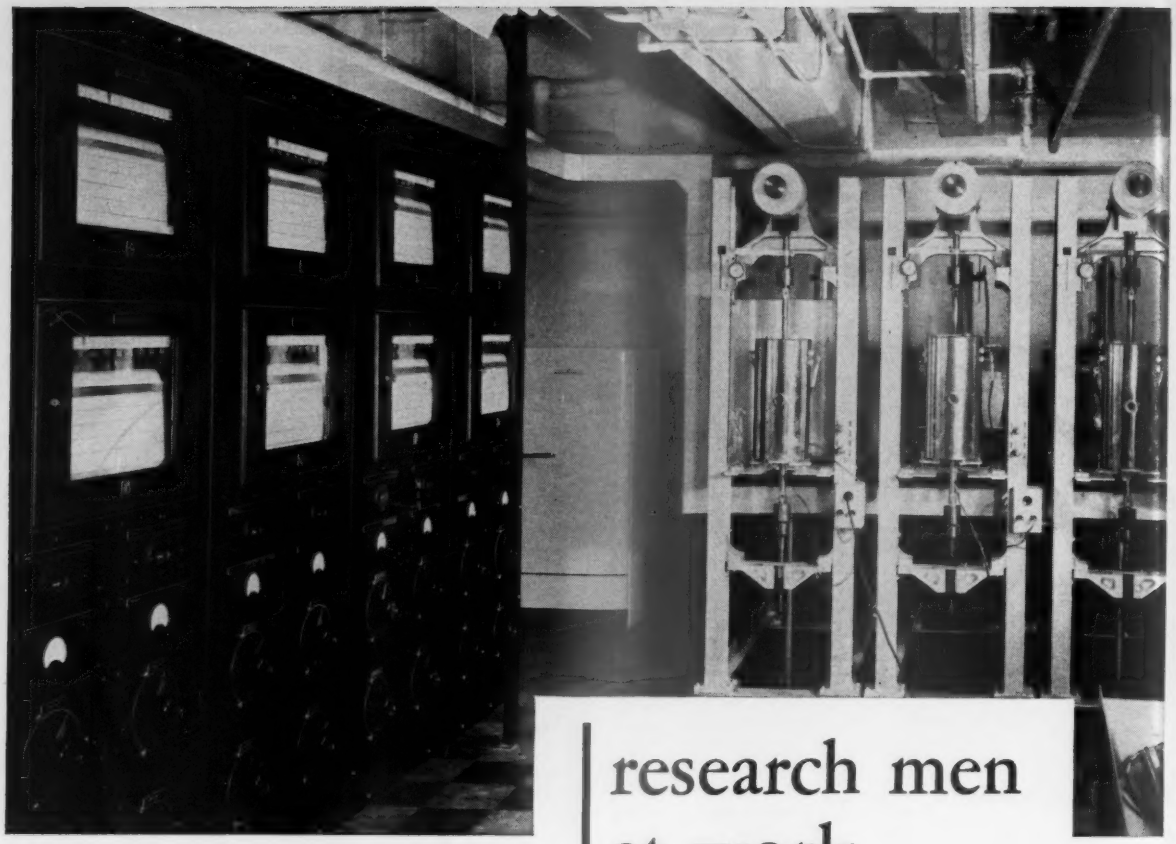

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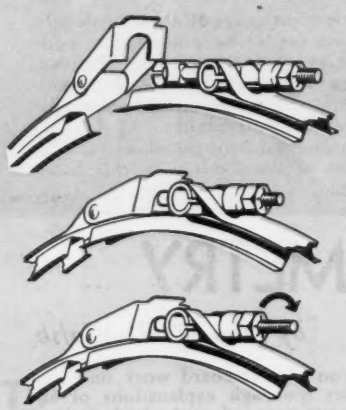

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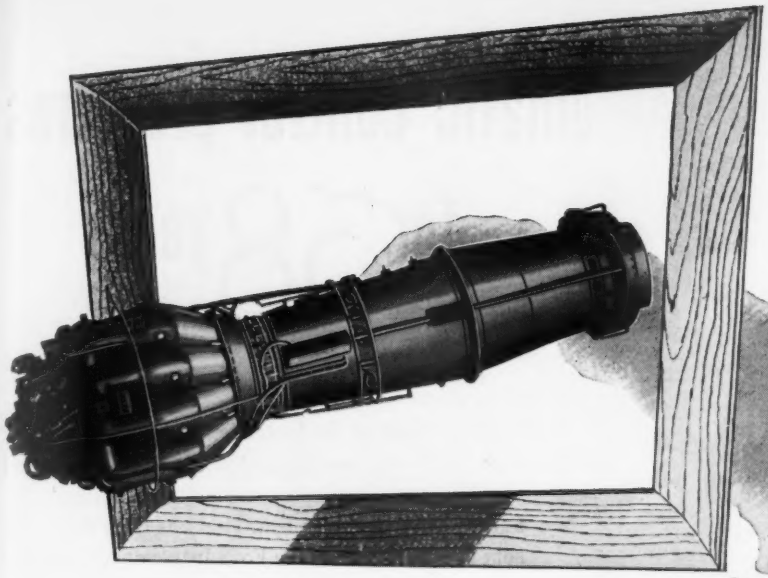

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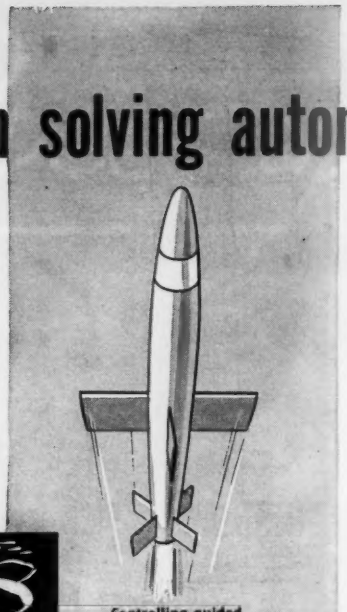

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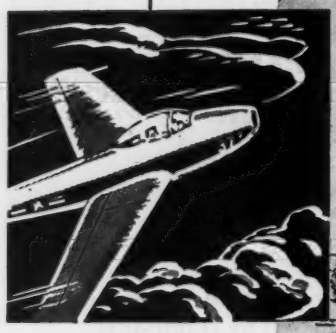

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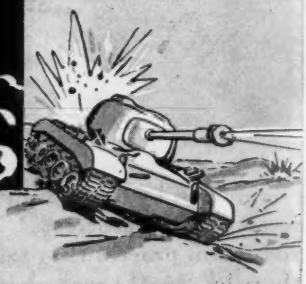

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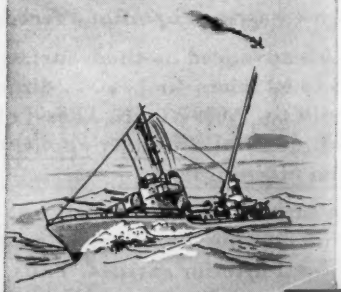

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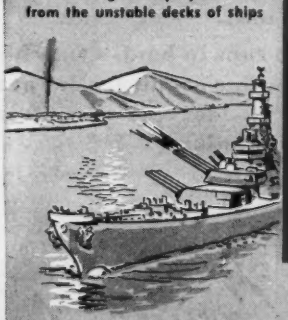

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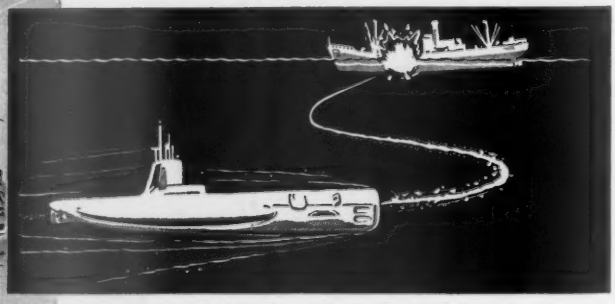

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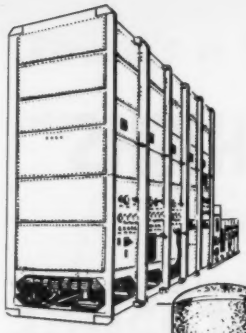
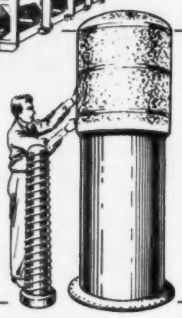


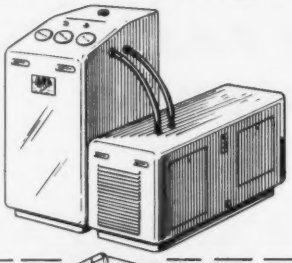
LIQUID OXYGEN GENERATORS

An air-transportable plant for the separation of high-purity oxygen from the air.



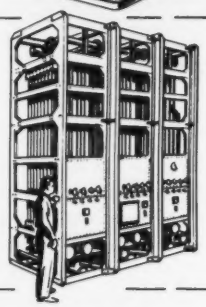
LIQUEFIED-GAS STORAGE CONTAINERS

Containers for the storage or transport of liquefied gases such as liquid hydrogen or oxygen.



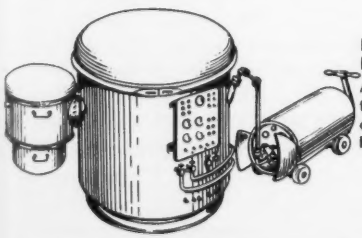
LIQUID OXYGEN PUMPS

A compact, noncontaminating unit for supplying high-pressure oxygen gas from low-pressure liquid oxygen storage containers.



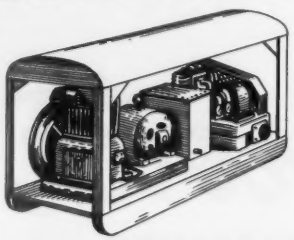
HEAT EXCHANGERS

A gas-to-gas heat exchanger with exceptional characteristics.



HELIUM REFRIGERATORS

A practical system for the prevention of evaporation loss in stored liquefied gases.



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A unit which provides cooled, compressed air which is free of dirt, oil, or entrained water.

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Our staff is experienced in interpreting the ideas of industry and following through with the perfection of specialized equipment.

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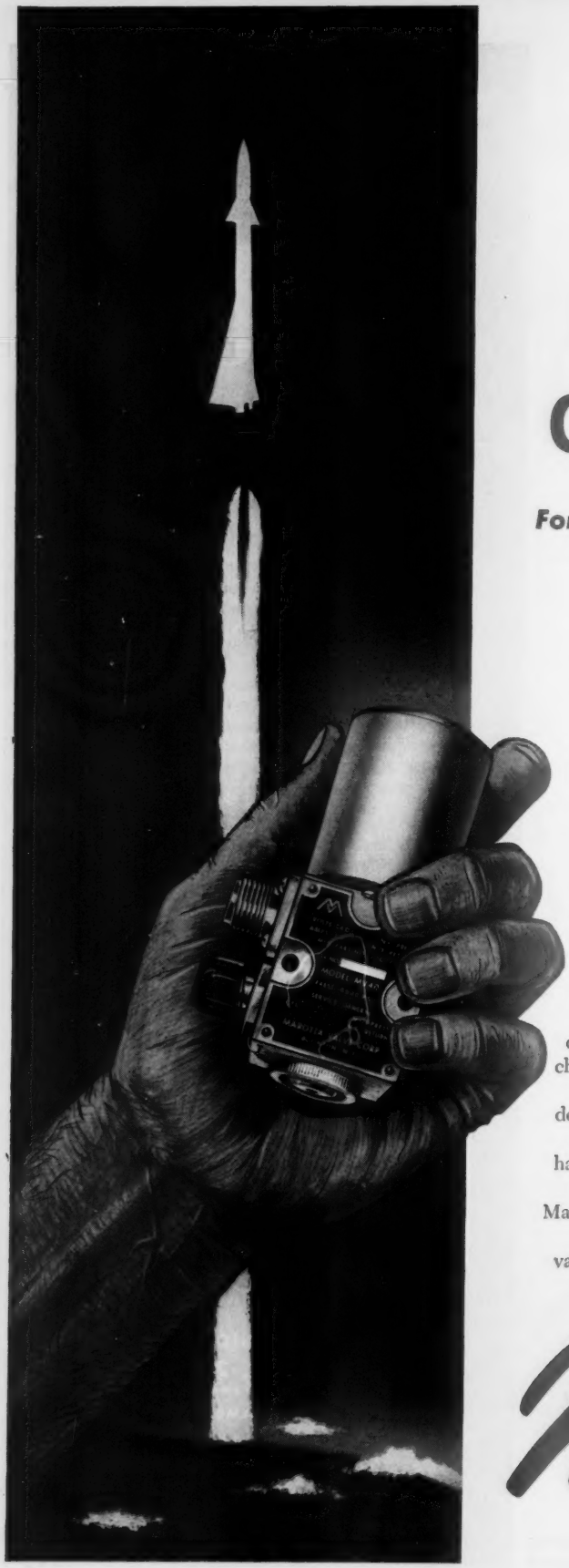

NEW HIGHS
FOR
HIGH PRESSURE CONTROL VALVES

For Rocket and Missile Applications

6000 P.S.I.
HIGH PERFORMANCE
COMPACTNESS
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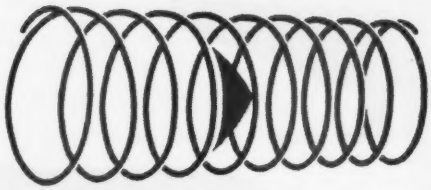
You're looking at the new MV40D magnetic control valve, another example of how Marotta's engineers are keeping pace with the rapid advances of rocket power and its ever changing demands. In the MV40D valve Marotta has met the challenge of higher pressure control requirements while maintaining minimum size and weight. Marotta has developed many other new control valves with outstanding performance characteristics. Many of these valves have been adapted to other industrial purposes where efficiency and reliability are important. That is why Marotta is recognized as one of the foremost manufacturers of specialized control valves. If you have a valve problem, contact us. We have the ability and experience to meet your most exacting requirements.

Marotta

VALVE CORPORATION
Boonton, New Jersey

There's a 10-turn Helipot to meet your requirements



With the development of the original HELIPOT—the *first* multi-turn potentiometer—an entirely new principle of potentiometer design was introduced to the electronic industry. It made possible variable resistors combining high resolution and high precision in panel space no greater than that required for conventional single-turn potentiometers.

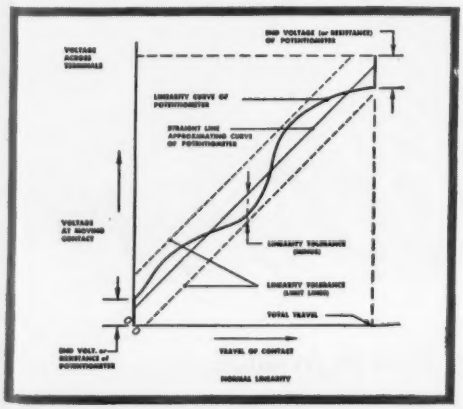
The Helipot Principle... *High resolution and precision settings require a long slide wire. But by coiling a resistance element into a helix, it is possible to gain desired resolution and precision without wasting panel space. This principle is applied in various Helipot models with slide wires ranging from 3 to 40 helical turns.*

Advantages are immediately apparent. In the case of the widely-used 10-turn Model A Helipot, for example, a 45" long slide wire—coiled into ten helical turns—is fitted into a case 1¾" in diameter, and 2" in length. Another advantage of the 10-turn pot is that, when equipped with a turns-indicating RA Precision DUODIAL, slider position can be read directly as a decimal, or percentage, of total coil length traversed.

10-TURN HELIPOT MODELS—CONDENSED SPECIFICATIONS

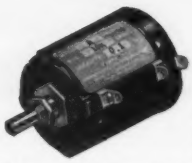
	Model A	Model AN	Model AJ
No. of turns	10	10	10
Resistance Range	10 ohms to 300,000 ohms	100 ohms to 250,000 ohms	100 ohms to 50,000 ohms
Resistance Tolerance: Standard	±5%	±5%	±5%
Best	±1%	±1%	±3%
*Linearity Tolerance: Standard	±0.5%	±0.5%	±0.5%
Best	±0.05% (1K ohms and above)	±0.025% (5K ohms and above)	±0.1% (above 5K ohms)
Power rating @ 40°C	5 watts	5 watts	2 watts
Mechanical Rotation	3600° +4° −0°	3600° +1° −0°	3600° +12° −0°
Electrical Rotation	3600° +4° −0°	3600° +1° −0°	3600° +12° −0°
Starting Torque	2 oz. in.	1.0±.3 oz. in.	.75 oz. in.
Running Torque	1.5 oz. in.	0.6±.3 oz. in.	.60 oz. in.
Net Weight	4 oz.	4 oz.	1 oz.

*i.e. INDEPENDENT LINEARITY. The above linearity tolerances are based on the following definition recently proposed to clarify and standardize nomenclature related to precision variable resistors. . . . "Independent linearity is the maximum deviation in percent of the total electrical output of the actual electrical output at any point from the best straight line drawn through the output versus rotation curve. (This line shall be measured through the extent of the effective electrical angle.) The slope and position of the straight line from which the linearity deviations are measured must be so adjusted as to minimize these deviations."



10-Turn Helipot Highlights

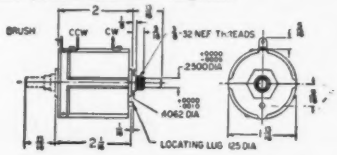
From the basic Helipot principle, model variations have been developed to meet new requirements:



Model A Helipot

the original 10-turn Helipot—provides a resolution from 12 to 14 times that of conventional single-turn potentiometers of same diameter (1¾"), linearities as close as ±0.05% in resistances as low as 1K ohms.

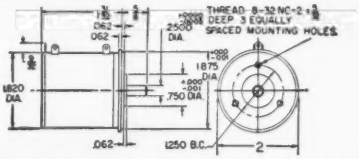
The same multi-turn principle is also available in 3 turn units (Model C), and larger-diameter units of 15 turns (Model B), 25 turns (Model D), and 40 turns (Model E)—a type for every application from 5 ohms to 1 megohm.

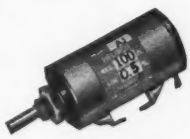


Model AN Helipot

an ultra-precision version of the basic 10-turn Helipot. Produced in volume to extremely close electrical and mechanical tolerances, this unit features precision ball bearings (Class 5), servo mounting lid, plus linearity tolerance as close as ±0.025% as low as 5K. A 3-turn unit (Model CN) is also available.

Models AN and CN are particularly recommended for precise servo-mechanism applications and represent the most advanced design and highest quality available today in the field of precision potentiometers.

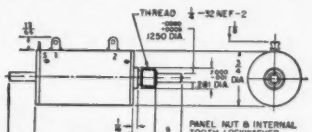




Model AJ Helipot

a 10-turn *miniature* Helipot only ¾" in diameter, weighs 1 oz., has slide wire 18" long. Also available with servo mounting (Model AJS) and servo mounting with *ball* bearings (Model AJSP). Linearities as close as ±0.1% as low as 5K.

Designed for long life under severe operating conditions, the AJ Series is widely used where small size and weight are vital.



Design details on above units are subject to change without notice. Certified drawings available upon request.

Only Helipot is able to supply—in volume—multi-turn helical potentiometers *with special features to meet your particular needs* . . . Special Shafts, Extra Spot Welded Taps at any position, Ganged Assemblies (except AJ), Special Temperature Coefficients, etc. Send us your requirements!

Contact your nearest HELIPOT representative for complete details—or write direct for Data File 506.

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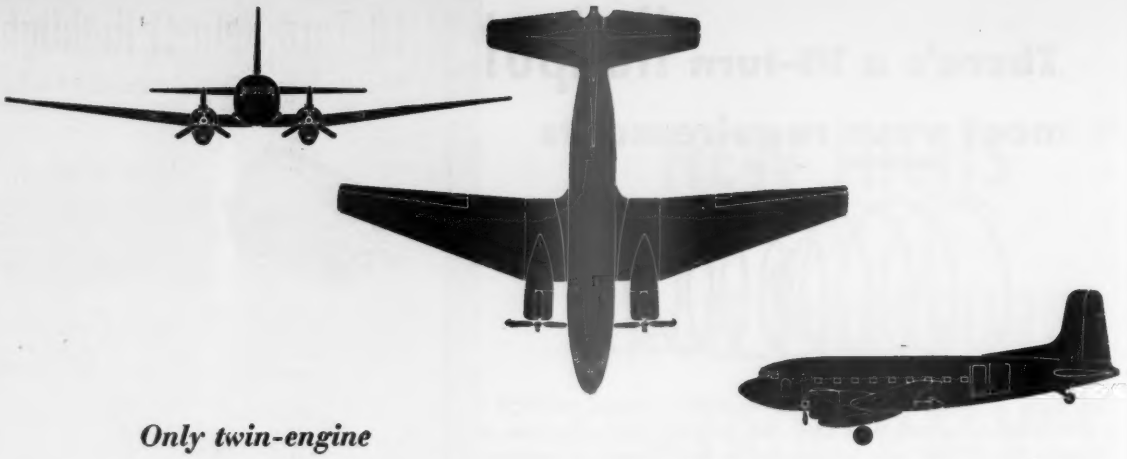

Only twin-engine

transport that makes regular flights

to Hawaii, the Navy's

Douglas R4D-8

Unique among twin-engine aircraft is the Navy's Douglas R4D-8. On orders, this transport can take off at San Francisco and safely wing its way across 2,562 miles of open Pacific to Hawaii.

Born of the Douglas DC-3, world's best known airplane, R4D-8 is longer, more powerful and flies on new swept wings. It carries 2,800 more pounds of payload 45 m.p.h. faster than its famous parent. Ceiling and range are greater. Passenger and freight loading are easier, quicker. And along with its improved performance, the Douglas R4D-8 still combines DC-3 reliability with twin-engine economy.

Development of the R4D-8 is another example of Douglas leadership in aviation. Planes that can be produced in quantity to fly *faster and farther with a bigger payload* are a basic Douglas rule.

Enlist to fly with the U.S. Navy

Depend on *DOUGLAS* **First in Aviation**

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NEW POTTER FLOWMETERS for ACCURATE TEST DATA

New Frequency Converter Models Have High Performance Characteristics

Now, improved models of the Potter Electronic Frequency Converter make it possible to utilize more fully the accuracy and sensitivity of the unique Potter Flow Sensing Element.

Greater stability over a wider temperature range, freedom from drift due to line voltage changes, faster response speed and longer life have been built into all the new units.

New models of the laboratory-type converter incorporate such features as adjustability for density changes from Specific Gravity .6 to 1.6, multiple-input models for measuring the output of one of a number of sensing elements, dual output jacks, integral 100 cps frequency standard, switch for dividing frequency of input signal by 0.5, 1, 2, 4, 8 and 16.

LABORATORY FLOWMETER SYSTEM consisting of Flow Sensing Element, Model 12-(1) Electronic Converter adjustable for density from Sp. Gr. .6 to 1.600, and indicating milliammeter. High-speed recorder, electronic potentiometer or other type of instrument can be substituted for milliammeter.

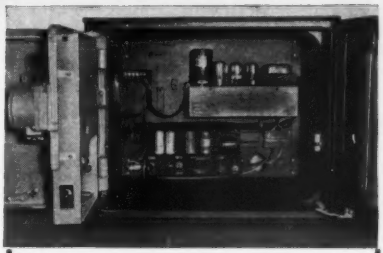
SPECIFICATIONS

Input signal range: 5 to 3200 cps.
Input sensitivity: .005 to 5.0 volts rms.
Drift: Blower-cooled to eliminate thermal drift. Less than .25% drift for 5 volt power drift.
Calibration frequency: Integral 100 cps (± .15 cycles) tuning fork standard.
Linearity: Within .1% at all points within operating range.
Adjustability: Full-scale deflection for frequencies from 50 to 3200 cps.
Specific Gravity Adjustment: Ten-turn Helipot, from .600 to 1.600.
Multiple-Input: Available with 1 to 5 input chanels.
Totalizer: Single-channel unit available with integral six-digit counter.
Instruments: Can be used to operate electronic potentiometer, high-speed recorder, or any 0-1 ma dc instrument.

New Potter Electronic Totalizer counts total number of output pulses produced by Flow Sensing Element. Instrument has six-digit counter plus two banks of decade read-out lamps; counts up to 99,999,999 pulses. Equipped with resets for counter and read-outs, and start-stop switch to facilitate counting over timed interval.

TACHOMETERS

Any of the Potter Frequency Converters can be used as a tachometer to measure frequency of pulses produced by a rotating magnet. Systems for both laboratory and industrial applications are inherently explosion-proof at sensing element location, accurate, easily installed, and adjustable to read or record directly in rpm.



INDUSTRIAL MODEL OF THE Potter Electronic Frequency Converter is mounted directly inside the case of Electronic Potentiometer. Instrument can be recorder, indicator or controller.

SPECIFICATIONS

Input signal range: 10 to 600 cps.
Input sensitivity: 5 mv to 200 volts.
Drift: Thermal drift less than .1% from 40 to 120° F. ambient. Negligible drift from 75 to 135 volts.
Calibration frequency: 60 and 120 cycles from line current.
Adjustability: Full-scale deflection for input from 80 to 600 cps.
Specific Gravity Adjustment: Available from 0.700 to 1.000.
Multiple-input: Available with 1 to 8 input channels.
Instruments: Can be used with any industrial model Electronic potentiometer; Precision Indicator, Circular Chart Recorder, Strip Chart Recorder.

The NEW Industrial Model single-range Potter Electronic Frequency Converter amounts directly inside an electronic indicating or recording potentiometer, uses line frequency as a standard for calibration.

Because both the signal voltage and the bridge energizing voltage are supplied from the same source, the effects of line voltage variations are completely eliminated.

The industrial model converter, installed in an *ElectroniK* Precision Indicator and used with Potter Flow Sensing Elements, has been thoroughly tested at many of the foremost air research centers. System accuracy, according to users reports is within ½%.

Systems accuracies within ±.1% have been obtained during tests of several weeks duration.

Send for further information.

POTTER
AERONAUTICAL CO.
87 Academy Street, Newark 2, N. J.

We took our cue from Mother Nature...

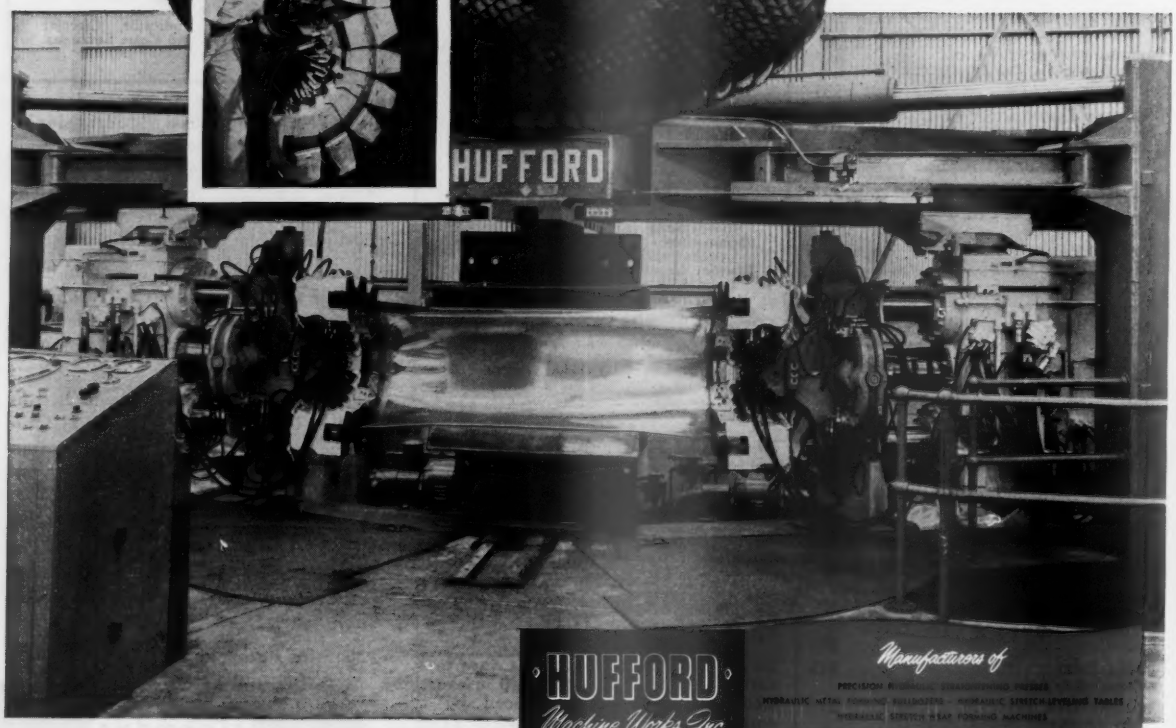
and built FLEXIBILITY into Hufford HYDRA-CURVE Jaws

Up 'til now, all sheets were gripped and maintained in a straight line during stretch-forming. Then a simple observation opened the door to untold savings in material. *If the sheet could be pre-curved to match the cross-sectional die curve, both cross-sectional and longitudinal curvatures could be formed easier, with fewer local strains and with considerable material savings per part!*

Hufford HYDRA-CURVE Jaws accomplish this fact. They are quickly loaded because all segments assume a straight, in-line position. With hydraulic power the flexible jaws then pre-curve the sheet before stretch-forming.

Since HYDRA-CURVING effects a far more uniform distribution of stresses, local strains are reduced and less failures result. Deeper curves are easily formed and *less material is lost in trimming.* Material savings up to 30% are possible. *Dollarwise, these savings alone frequently cover jaw costs in the first year's operation!*

Our new FREE FOLDER describes many other HYDRA-CURVE advantages. Let us send it today!



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Missile with a "one track mind" ...Bomber Defense

Defensive guided missiles launched from supersonic aircraft will depend upon electronic marvels that come as close to simulating human intelligence as any mechanism ever devised. Important functions of these "weapons of the future" are typical of those entrusted to systems made by Arma Corporation.

Complex electronic and electro-mechanical controls from Arma are an integral part of many of America's most advanced weapons. In basic research, design, development and manufacture, Arma Corporation has worked in close cooperation with the Armed Forces since 1918—and more recently, the Atomic Energy Commission. ***Arma Corporation, Brooklyn, N. Y.; Mineola, N. Y. Subsidiary of American Bosch Corporation.***

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